WHITE PAPER ON RF ENABLING 6G – OPPORTUNITIES AND CHALLENGES FROM TECHNOLOGY TO SPECTRUM

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*) The chapter editor passed away during the preparation of this white paper.


Stop:300.000MHz
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Executive summary

Many visions of 6G and the evolution of data rates in wireless systems in general are directing their vectors toward Tbps communications by 2030. This target, with the important goal of sustainable development in the future world, will inevitably lead to many questions within the RF community about whether this will be feasible at all, and how. As the same question is also raised by other experts from various fields, this paper will examine the challenges and opportunities before us from many perspectives. It is evident that 6G will not only be extremely high-speed communications. For example, the existing wireless infrastructure and new solutions in ultra-low power communications will also live and evolve, further enriching the fabric of wireless systems serving an even wider spread of applications.

6G is also expected to merge communications and sensing in a new way, and the wide bandwidth needed for data will also benefit many high-precision sensing applications. Multi-use, scalability, and energy efficiency will be of the utmost importance, and the tradeoffs will be neither straightforward nor easy to implement, or even understand, without a deep dive into key technologies. These are evolving mostly from the well-established solutions in the market, but at the same time, the need for something completely new is evident. The gap between radio and optical communications is also narrowing, potentially answering some of the concerns.

This white paper will not only discuss the opportunities but also the serious challenges that are foreseeable in the technology community. These may slow down, or in the worst case even block, some of the development paths. How we cope with such threats and use the existing opportunities in the engineering process from early research to final products in the current landscape is one of the key questions that will be asked by the RF community. At the end of this paper, a list of refined questions will be shared. These are not for the RF community alone, but for experts working in various disciplines and stakeholders that are together building the future of 6G enabled by radio technologies.

Introduction 1

Wireless data rates have doubled every eighteen months over the last three decades, as predicted by Edholm's law. Direct extrapolation from [KP13] predicts that Terabit-per-second (Tbps) link speed will even be achieved before 2030, facilitating capacity well beyond current optical networks. To support the prediction, standardization especially in Wireless Local Area Networks (WLAN i.e. 802.11 family) and high-rate Wireless Speciality Networks (WSN i.e. 802.15.3 family) is moving gradually from tens of Gbps beyond 100 Gbps. However, practical trials have shown that state-of-the-art radio links can approach the 100 Gbps milestone only at a 1–2 m distance over fixed links without beam steerability [RLG20]. This means that taking the next 1,000x increase in link capacity from 1 Gbps to 1 Tbps in practical networks will be a far from straightforward challenge for the next 5 to 10 years, especially for wide area but even for shorter-range mobile coverage.

Physical and financial constraints are setting strict boundaries, and as the continuum of Moore's law, Edholm's law, relying strongly on the former, requires the favorable and rapid development of core technologies from semiconductor processes to complete chipsets and other associated components like antennas to keep the past trend moving forward. In addition to the availability of spectrum, facilitating the development is essential. As radio communications is approaching the Tbps challenge by going to higher frequencies, the other trend is that optical communications is gradually expanding from wireline to wireless solutions, examining the problem from a different direction.

Advanced physical layer solutions and more importantly, new spectral bands and hardware (HW) technologies to provide adequate performance, will be required to support these extremely high data rates. In this context, the Terahertz region is envisioned as a key wireless technology enabler to satisfy this demand, by alleviating spectrum scarcity and capacity limitations of current wireless systems, and enabling a plethora of long-awaited applications in diverse fields.

The definition of the THz band seems to vary in the literature, although the ITU definition of the THF (tremendously high frequency) region holds that the scientific definition of the THz band is from 0.3 THz to 3 THz [WIK20]. One should note that the definition of the THz band in many recent papers spans the frequencies between 0.1 THz and 10 THz, and it remains one of the least explored frequency bands for communications [AJH14]. To avoid unnecessary conflicts with ITU definitions, we call the higher end of the EHF (extremely high frequency) band the upper mmW band or region. The band covers frequencies of 100–300 GHz, and it will probably be the most interesting band in the coming years for the research of new radio communications systems. The region provides a much larger portion of spectrum than the lower mmW region (30–100 GHz). The latter has also already been extensively adopted by many standards, including 3 GPP 5G NR (new radio), 802.11, and various radar systems.

Wireless technologies that include a lower mmW region are unable to support Tbps links. On the one hand, advanced digital modulations, e.g. Orthogonal Frequency Division Multiplexing (OFDM), and sophisticated communication schemes, e.g. very large-scale Multiple Input Multiple Output (MIMO) systems, are being used to achieve a very high spectral efficiency at frequencies below 5 GHz. However, the scarcity of the available bandwidth limits the achievable data rates. For example, in Long-Term Evolution Advanced (LTE-A) networks, peak data rates in the order of 1 Gbps are possible when using a four-by-four MIMO scheme over a 100 MHz aggregated bandwidth. These data rates are three orders of magnitude below the anticipated 1 Tbps. However, millimeter wave (mm-Wave) communication systems such as those at 60 GHz can support data rates in the order of 10 Gbps within one meter [RMG11], or nowadays even more. While this is one path to follow, this data rate is still two orders of magnitude below the expected demand.

This paper covers a wide range of aspects in the path toward Tbps communications and sensing, from spectrum and radio channel to enabling HW technologies, including semiconductor circuits, antennas, packaging, and the testing of transceivers approaching the THz region. Opportunities in optical communications will also be discussed to close the "THz gap" from both ends of the spectrum. The broad scope of radio frequency (RF) and optical technologies deserves a more extensive view of the digital signal processing aspects, including the future of Moore's law, because broadband communications depend heavily on this evolution. Unfortunately, space is limited here, so the reader is advised to examine other sources like [MA17] and [DFS20].

Precise targets for 6G are not yet defined, but visions, use cases, and key values are being extensively discussed globally, in addition to relevant and potential technologies [HUH21]. They already indicate major needs to develop RF technologies well beyond the current state of the art. Of course, much will also be reused from the existing generations, but we need at the same time to address the challenges in which current technologies cannot meet the future demands, and the roadmap is not obvious, with many alternative scenarios for the technical solutions. This imposes major challenges for the RF community to overcome the challenges, while keeping the system complexity manageable.

6G system and spectrum considerations and potential applications

2

2.1 6G system considerations

With the massive commercialization of 5G worldwide, new requirements and technologies for the next network generation are already appearing on the agenda. The first global vision for 6G presented in [LL19] depicts 6G as a framework of services in which the communication service is integrated with sensing, imaging, and highly accurate positioning capabilities and mobility. Continuously improving the performance of transmission while enabling the capabilities of these other services in the 6G network are key directions in 6G research. The capability of 6G link transmission is expected to be improved by at least 10–100 times that of 5G to achieve a terabit per second (Tbps) target and support the throughput demands of data-rate-intensive applications such as holographic communications, virtual reality (VR)/augmented reality (AR), and so on. In addition to the advanced radio interface technologies that aim to improve spectral efficiency, such as waveform and modulation, widening the frequency bandwidths and considering a variety of carrier frequencies are needed. As spectral efficiency is a controversial target at extremely high frequencies and bandwidths, an appropriate compromise for the best system efficiency, including the minimization of total power consumption, should be the primary focus.

When we start to consider 6G requirements from the radio performance perspective, the essential requirements are a high throughput (at least Tbps), an adequate distance (no less than 1 km), and mobility. In going to higher frequencies like the upper millimeter wave (mmW) and terahertz (THz) bands with mobility, the range is likely to be rather limited. Power dissipation and limited output power with higher transistor noise makes tradeoffs in system design more difficult. Algorithms for detection and beam scanning also need to adapt to very fast and small changes in signal environment due to small wavelength. These system considerations, in addition to other traditional mobile communication system KPIs like connection density and latency, should already be considered in the early phase of 6G research and prototyping. This leads to the entirely new topic of the development of new indicators for the 6G era that are also discussed in [LL19], [MAA20], [PBP20].

2.2 Spectrum considerations

The spectrum bands currently used for 5G and prior generations of cellular mobile communication systems continue to be potential bands for deploying future 6G systems. Additionally, upper mmW and THz frequencies are recognized as of interest for 6G. To meet the needs of increasing transmission rates, 6G systems will be able to transmit and receive signals in multiple different frequency regions (cmW, mmW, and THz). The higher and lower frequencies have their pros and cons, which can be smartly utilized in serving different applications. Higher frequencies, including mmW and THz frequencies, offer vastly improved data rates compared to lower ones (especially frequencies below 3.5 GHz) through wider bandwidth availability. Higher frequencies offer a high data rate for short-range connectivity that also entails a high frequency reuse factor, allowing improvement in network densification and throughput, as well as sharing the spectrum with other systems. Going to the upper mmW band (100–300 GHz), and in the future also to the THz band (>300 GHz), network throughput and resource sharing among users could be pushed far beyond that of the current 5G systems, especially in densely populated areas. Note that the bottleneck of mmW communications is mainly from network coverage. In addition to increased throughput, relevant technologies to resolve the coverage issue must therefore be developed in the future network. Due to antenna physics, explained later in detail, the signal transmission in the THz region is more difficult than that in the mmW. However, it still has potential via gain compensation through advanced antenna technologies. Furthermore, between 30 GHz and the THz region, the increase in free-space loss is very limited. A remaining challenge is to make cost-effective and power-efficient implementation technologies available at that frequency range. Challenges related to this will be discussed later in this white paper

To achieve Tbps transmission capacity, a true THz communication system that includes all the necessary components, from antenna and RF components, through AD/DA conversion to digital signal processing, becomes attractive. Although commercial systems for mobile connectivity well above 10Gbps are not yet available, recent research has demonstrated the first signs of peer-to-peer (P2P) systems for backhaul application. Some experiments in Europe, East Asia, and America using upper mmW or THz technology have achieved link capacity in the range of 100 Gbps, at least for a short distance, while when the 6G vision is considered, further improvements are needed. However, considering the attenuation in the air, available output power, and receiver sensitivity, the current RF integrated circuit technologies are not yet sufficiently mature or economical for Tbps for long-distance transmission.

However, one might suppose that terahertz coverage is limited to short-range applications due to e.g. atmospheric attenuation. Overall, atmospheric attenuation constantly increases with increasing frequency. If atmospheric attenuation exceeds 10 dB at 1 km, kilometer-class wireless communication will be difficult. Such frequency bands are the 60 GHz band due to oxygen absorption, and the 183 GHz and 325 GHz bands due to atmospheric moisture, Figure 2.1. Atmospheric attenuation also exceeds 10 dB/km at all frequencies above 351 GHz. The influence of atmospheric attenuation at 1 km is not significant at other frequencies. Between 252 and 296 GHz, the distance at which atmospheric attenuation is 10 dB exceeds 2 km, as shown in Figure 2.2. With this definition of the frequency band between 192 GHz and 298 GHz, the communication distance is more than 2 km, and in the frequency band from 121 GHz to 154 GHz, the communication distance is more than 8 km. However, it should be noted that the communication distance will be shorter when it is raining: The calculation is based on the attenuation of the atmosphere when it is not raining. But it is still noteworthy that there is a possibility of wireless communication in the kilometer range.

Meanwhile, lower frequencies offer the great benefit of greater distances and MIMO techniques that can greatly improve spectral efficiency. They also have the ability to serve cell edge or remote users, and are mostly enough to serve the vast majority of applications. Ulti-

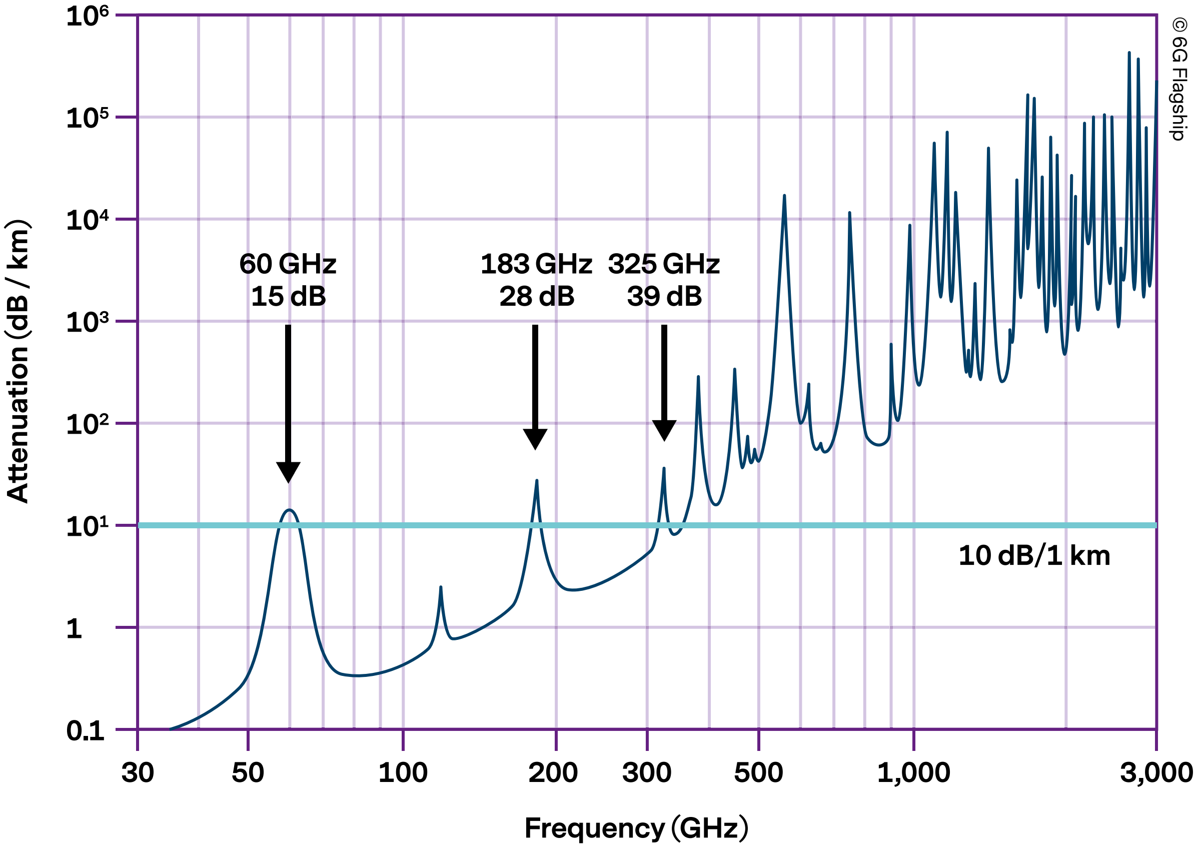


Figure 2.1. Atmospheric attenuation of radio waves from 30 GHz to 3 THz.

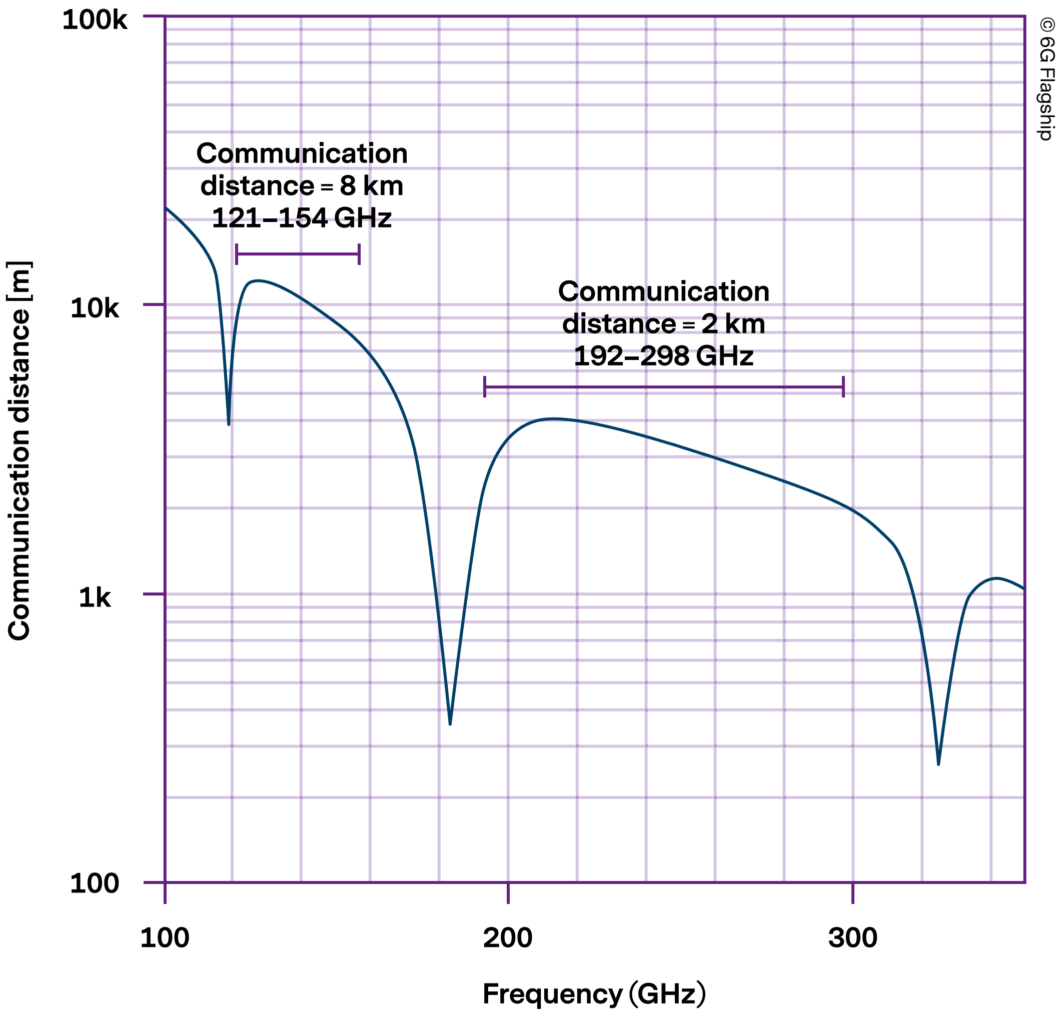


Figure 2.2. Communication distance from 100 GHz to 350 GHz.

mately, different applications can utilize different parts of the spectrum simultaneously. Of course, there is a major challenge to doing this energy efficiently. Control of the large variety of applications and the different frequency bands with their own characteristics is a major research challenge.

More details on the use of spectrum and spectrum sharing are given in Chapter 7.

2.3 Potential applications

The higher the frequency, the faster the channel will change, creating a challenging network resource optimization problem. Another degree of difficulty will be set by the emerging applications and use cases in the future. There are almost as many sets of requirements for the wireless connection as there are applications and use cases. To provide robust connectivity, 6G systems will have to be able to adapt to these new use cases and varying user behavior. Potential applications of 6G have been discussed earlier in [LBB20], [MLP20], [RAB20], [SDA20], [TAY20]. This does not always mean Gbps or Tbps connectivity, but it means enough to serve users, and the large variety of use cases and applications. Here we focus on a set of applications that could especially benefit from the use of higher frequencies.

When the data rate is considered from the perspective of applications served, mmW and THz frequencies can satisfy the needs of extremely data-hungry applications such as augmented or virtual reality (AR/VR), data kiosks, and general broadband home connectivity. Despite the atmospheric attenuation, mmW and THz have the advantages of accurate ranging and positioning, and the ability to work at all times, regardless of the weather. Moreover, mmW and THz can effectively detect a variety of materials. Yet medical and security devices based on millimeter wave and terahertz bands are being developed. Millimeter wave and terahertz have the characteristics of penetration, high resolution imaging, and nondestructive detection. Meanwhile, different materials or substances have different frequency points of impulse response in millimeter wave and terahertz bands. These characteristics give it wide application potential in the security, building, and disease detection fields.

Long-distance backhaul using THz communication

The speed of wireless communication will not be significantly inferior to that of fiberoptic or wired communication using THz communication. Currently, the communication infrastructure is maintained with optical fibers, but fiberoptic networks will spread to places with currently restricted communication, such as the sky, space, or at sea. Terahertz communication can be used to create powerful links that act as if optical fibers were connecting satellites or connecting the ground and satellites.

When THz communication is used for the backbone network, it is necessary to improve the basic performance by increasing the output power and receiving sensitivity, for example. Further, beam steering technology is the key to THz communication on the premise of a high-gain antenna. When THz communication is used for a backbone network or low earth orbit (LEO) communications, beam steering is required even for a fixed station to facilitate installation, and its development will be important in the future. However, the steering width may not need to be wide, and high-speed tracking may not be required.

Sensing networks

Connected intelligence is another application area for 6G, including spanning a variety of use cases that could benefit from the use of sensing networks, in which network infrastructure and different devices are equipped with sensing capabilities (see [LBB20] for more information). Integrating sensing functions with the base stations (BSs) of the mature communication networks is an effective technical way of building a 6G sensing network. The infrastructure-based sensing network can be applied to intelligent transportation, for example, by using the infrastructure deployed close to a road or intersection to sense the status of traffic nearby and then sharing this information in the network to realize traffic management intelligence. From the perspective of the terminal, to obtain sensing ability, methods that add various sensors like touch panel, camera, infrared, or gyroscope to the smartphone runs through the entire smartphone development history. In autonomous driving, for example, all the automotive radars on vehicles sense (detecting/positioning/imaging) the situation of the surrounding environment. The results are then uploaded to the network side via a wireless connection. Finally, the network guides or assists the vehicle's driving operation. From this process, sensing is the basic ability of intelligence and an important part of future 6G networks and devices.

An example of a new application is the 60 GHz millimeter wave radar system on a chip [GES1], which can be used to detect a limited set of hand gestures. It has been implemented in a commercial phone [GES2]. The development of millimeter wave radar chips brings plenty of new applications, including motion recognition, material detection, and 3-dimensional scanning imaging. Integrating millimeter wave radar chips with the mobile communication terminal can therefore greatly extend the scope of its application. However, sensing requires a huge bandwidth to be available. Due to resolution limitations, the gesture recognition rate of millimeter wave radar in a real environment is scarcely satisfactory. Given both the sensing ability and opportunity for extremely high-rate communications, the upper mmW or THz band therefore has potential.

Joint radar communication applications

Another application in higher-frequency bands is joint radar-communication [CHA16]. There is a trend of merging communication and radar systems. Communication systems are moving toward spectrum bands higher than 100 GHz that are suitable for high data-rate communication and high-resolution radar sensing. There is an increasing demand to integrate radar and communication functions in one system. In joint communication and radar, new and legacy applications need to coexist, given that they share the RF spectrum and co-design between communication and radar in new applications such as joint waveform designs and joint beamforming [CCF20].

Another trend in more intelligent communication networks is the automatic driving system for automobiles. In the early days of automatic driving development, millimeter wave radar has been applied in the field of anti-collision and driving assistance. However, the mature technology for autonomous vehicles needs to deal with a complex environment and have extremely low fault tolerance, which requires high precision sensors. Compared with millimeter wave, terahertz has higher frequency and can achieve broader bandwidth, providing super high-resolution imaging of pedestrians, vehicles, and obstacles. The characteristics of terahertz can improve the safety level of automatic driving technology. Meanwhile, an ultra-fast and low latency communication system can be installed in the car to upload data to the cloud. The intelligent cloud can guide the driving operation in return. Therefore, the upper mmW and terahertz ranges are preferred in the sensors for the automatic driving system for automobiles.

Transceivers and emerging communication concepts for 6G from link to platform

3

It is necessary to examine some fundamental aspects in communications when discussing Tbps data rates. Achieving the rates predicted by Edholm's law will be less simple in practice than one might suppose, for it is based on a law resulting from observation, not straightforward physics. Some key interdependences are described in Figure 3.1. High data rates directly impact bandwidth, and therefore carrier frequency and range. The transmitted power and noise will be impacted negatively, and the properties of the waveform—specifically, the required signal-to-noise-ratio (SNR) and envelope content, i.e. peak-to-average ratio (PAR)—will narrow down the usable dynamic range in the radio link as a contradiction with the target. An increase in total power consumption using equivalent technologies is also inevitable. Power per transmitted bit is therefore often considered an indicator of improvement. However, it is not a generically straightforward definition, because conceptually, it often only takes digital power consumption in the classical literature into account, ignoring link range and other aspects that might dominate the usability of the link. It is well known that in many comparisons, very short-range solutions outperform long distance links unfairly in this comparison. Therefore, one must also be very careful about the definition when this performance indicator is used.

In this chapter, we will discuss general aspects related to radio links and the RF transceivers implementing them. In the following chapters, we will examine the relevant RF technologies that need to be addressed on the journey to understanding opportunities and challenges related to Tbps communications. In addition, the speed of the digital signal processing forms another bottleneck that is only mentioned briefly in this paper's Introduction. This is not a trivial challenge either.

Here, the intention is not to claim that achieving 1 Tbps would be possible if we had unlimited resources in terms of cost, power consumption, and engineering. Instead, addressing the problem in an economical and sustainable manner will be a huge challenge for 6G by 2030. First, we should address the necessary bandwidth requirements from various perspectives.

If we take classical modulation schemes like quadrature amplitude modulation (QAM) as a starting point, as in Figure 3.2, we can see that the uppermost curve indicates that 1 Tbps of uncoded data actually requires 1 THz of bandwidth in a binary case. As we move to higher-order modulations with better spectral efficiency, the bandwidth reduces in the range of 170 GHz for 64 QAM. This still seems very hypothetical, given that the highest RF bands under consideration for 5G are in the range of 100 GHz, and even the lower mmW bands starting from ~24 GHz are just being ramped up commercially. In practice, this bandwidth requirement is then even wider for

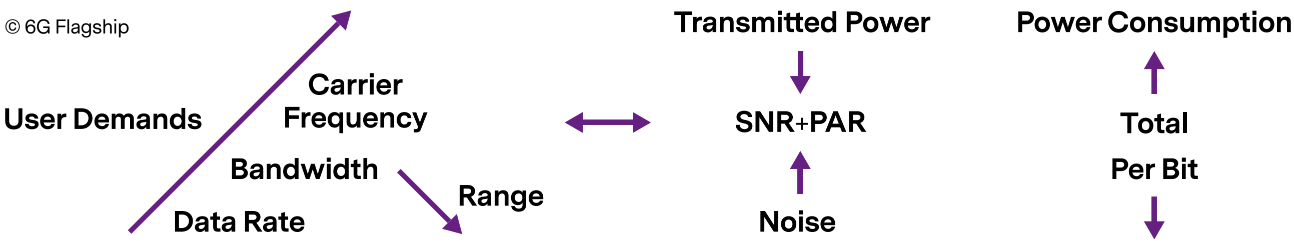


Figure 3.1. Key tradeoffs in radio system design toward higher data rates.

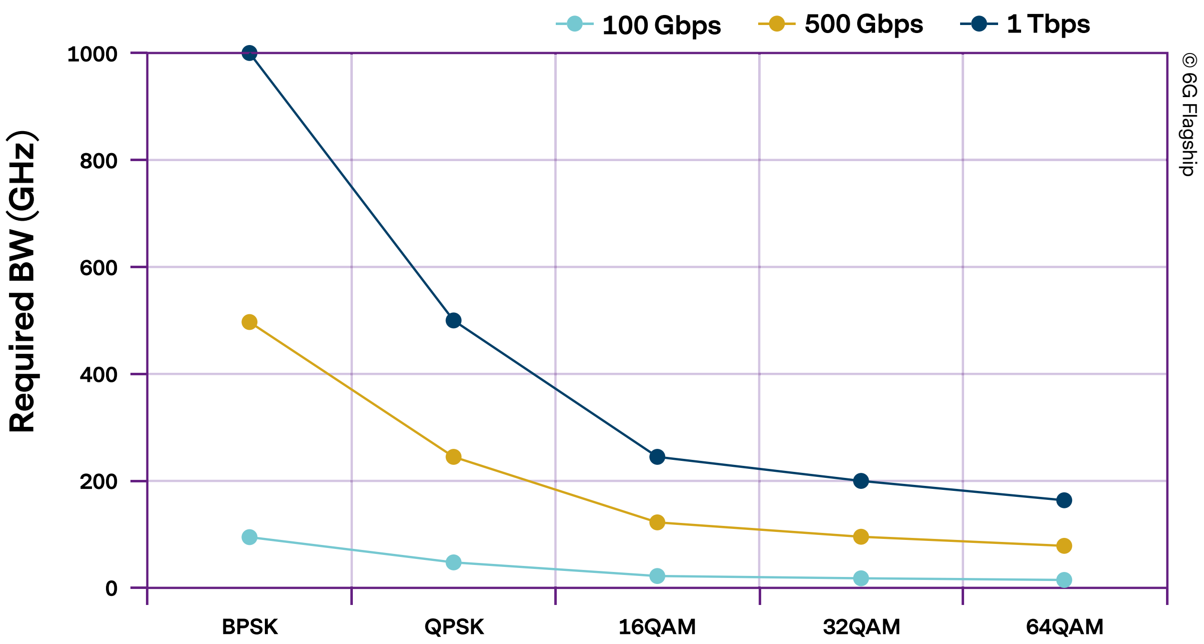


Figure 3.2. Toward Tbps – Required bandwidth for communications.

single carrier modulation due to the larger guard band compared with OFDM. Yet the digital signal processing (DSP) of OFDM signals consumes so much energy that it is unlikely to be a viable solution for any DSP in the foreseeable future. The required leap forward is huge and cannot be achieved by merely enhancing the carrier frequency. In addition, implementing extreme broadband RF circuits is difficult and typically leads to degraded performance. The effective channel bandwidth may be equally limited by bandpass response of RF blocks as well as low-pass (LP) characteristics of high-speed packages in the BB path [RGH20]. On-chip integration of high-quality passive components and antenna elements, although challenging, shows still an underestimated benefit in terms of considerably reduced packaging costs for high-frequency signal escape [LPG09]. The recent transceiver implementations at frequencies above 200 GHz, like [RGH19], are also bounded by a relative bandwidth in the range of 10-12%. This means that even in the upper mmW region, a single RF transceiver can support only a 20–30 GHz bandwidth, assuming such wideband A/D- and D/A-converters would be available with resolution of at least 6 bits, or preferably more. The technology boundaries of data converters will also be addressed in the following chapters.

Based on simple math, the bandwidth required for 1 Tbps communications needs to be split at least in six and preferably a larger number of parallel, not mutually interfering, orthogonal channels. The options of frequency separation, MIMO, or any other beamforming techniques are basically available —all of them with different tradeoffs. Frequency separation is of course the most traditional. However, finding many bands covering at least 20 GHz bandwidth or more is far from easy. Classical MIMO has several issues, and specifically, the complex DSP will be a major drawback compared to an RF/analog beamforming approach. Even then, the required parallelism and complexity of combining signals from different antennas and steer beams goes well beyond what has been seen in any communications or radar system below 100 GHz. Circular polarization diversity MIMO is yet another way to overcome these channel bandwidth limitations. Two orthogonal channels with 35 GHz have recently been demonstrated in [RGH20] with 110 Gbps at 230 GHz in a SiGe BiCMOS technology. One can conclude that no easy or obvious solution exists yet, even at the architecture level. Optimizing technologies, architectures, and waveforms collaboratively will therefore be one of the biggest challenges before 6G systems at extremely high data rates become feasible.

In addition to data rate and capacity, link range is one of the key aspects in radio system design. Furthermore, the fundamental tradeoff between range and data rate is unavoidable, because the higher spectral efficiency requires more signal-to-noise ratio (SNR), and a wider bandwidth will result in a higher noise floor. For these two simple reasons, link range is highly dictated by the data rate, in addition to the properties of the RF technologies. The details of the technology boundaries will be discussed in the following chapters, but the simple and logical consequence of the need for a higher carrier frequency for a higher bandwidth cannot be ignored. At higher carrier frequencies, it is much more difficult to generate more power for the transmission, and noise will be impacted negatively not only due to bandwidth but the fundamentally increased noise of the transistors as

a function of the carrier frequency [HGR19]. This was already very evident in the lower mmW region when 5G NR and other protocols did their system analysis. Achieving a decent range with realistic implementation constraints requires enhanced antenna gain, which is typically implemented with steerable phased arrays at a lower mmW range [STH17], [DHK18], [SHS19], [LPG09], as shown, for example, in Figure 3.3 for a transmitter. The practical solutions require more antennas in the range of tens to hundreds. At upper mmW frequencies, the link budget, even at relatively short ranges, needs lenses with integrated antenna solutions, making beam steering cumbersome [RGH19]. As the number of antennas is increasing exponentially, compensating for higher losses per antenna element when the frequency increases, achieving very high link ranges with antenna arrays becomes challenging even at relatively short indoor ranges. Yet theoretical analysis for various scenarios shows that indoor ranges may be possible even at a 300 GHz range, while very advanced lenses may be the only solution for km range communications—for example, in backhaul applications [RKL20]. These opportunities may become feasible in the future. However, the relatively simple early test beds, operating up to 100 Gbps, show very short ranges for single fixed links using electrical circuits [RLG20]. Industry and academia need to team up in the future to overcome this test and measurement bottleneck, in particular in large THz MIMO networks. With optical transmitters, the range could be somewhat improved, as shown in Figure 3.4 [DSP20]. However, it is evident that we are still far from achieving Tbps speed even in test beds with a relatively low technology readiness level. For mass volume consumer products, we still lack proven technologies for all areas, from digital, through packaging increasing the integration level, to antennas, which will be a challenge for both academia and industry in many ways in the coming years.

RF technologies and the use of spectrum are strongly impacted by potential new signal processing techniques for communications. As the impact on RF processing may be highly disruptive in some cases, this section lists some of the proposed techniques that may require significant rethinking in implementation aspects, as was the case earlier when moving from analog to digital communication in 2G or CDMA, and to OFDM and MIMO in later generations.

Some radical considerations appear in the literature for solving range, capacity, and performance issues—for example, using single-bit analog-to-digital converters (ADC) in massive MIMO communications [YLH18], [XQC20], [WWJ18], [XQG21] or circular polarization THz MIMO in [RGH20]. Another technology candidate, Orbital Angular Momentum (OAM), is an intrinsic physical property of Electro-Magnetic (EM) waves and is becoming a new dimension in wireless transmission. The orthogonality in OAM brings additional spectrum and energy efficiency, which was first discussed in the area with photons and light. In the last decade, OAM was employed at the radio frequency and was expected to be utilized in high-capacity Line-of-Sight (LOS) transmission. [CZL16], [LWW19], [YLZ19], [OSM15].

The typical applications of OAM in EM wave transmission can usually be classified in three categories, according to whether or not the OAM can be measured as the independent orthogonal dimension, the non-independent but orthogonal dimension, and the non-independent non-orthogonal dimension. Specifically, when OAM is used as the independent and orthogonal dimensions, the OAM spectrum can be established separately from the frequency spectrum. The independent orthogonal dimension usually refers to the OAM quantum transmission with OAM sensors, rather than as received by traditional antennas. The non-independent but orthogonal dimension refers to the Multiple Input Multiple Output (MIMO) transmission with the coaxial deployed special OAM antennas. Moreover, the non-independent non-orthogonal dimension often refers to the MIMO transmission with a coaxial Uniform Circular Array (UCA). In this circumstance, OAM is degenerated into the new Degrees of Freedom (DoF) for beam steering in MIMO transmission.

The third area of increasing interest is reconfigurable intelligent surfaces (RIS) using metamaterials [HZD20],

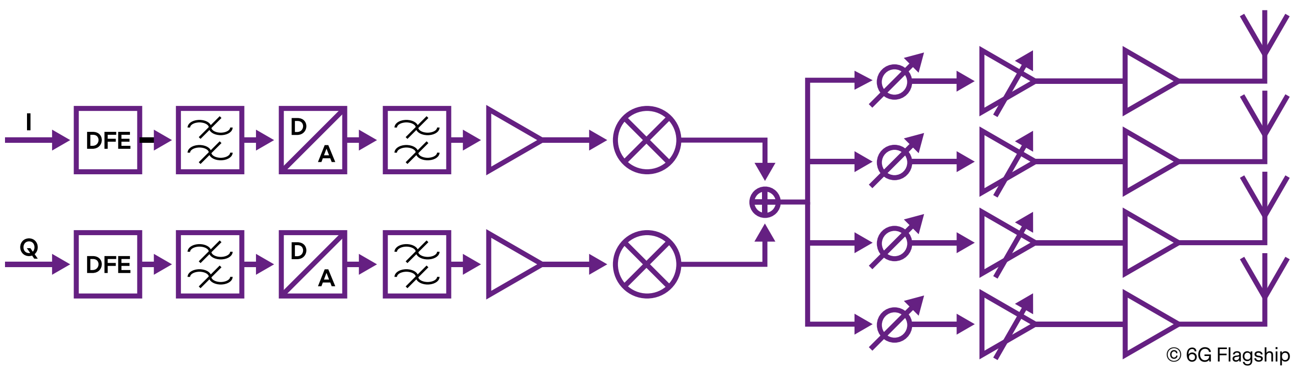


Figure 3.3. Four-antenna phased array transmitter with RF beam steering capability.

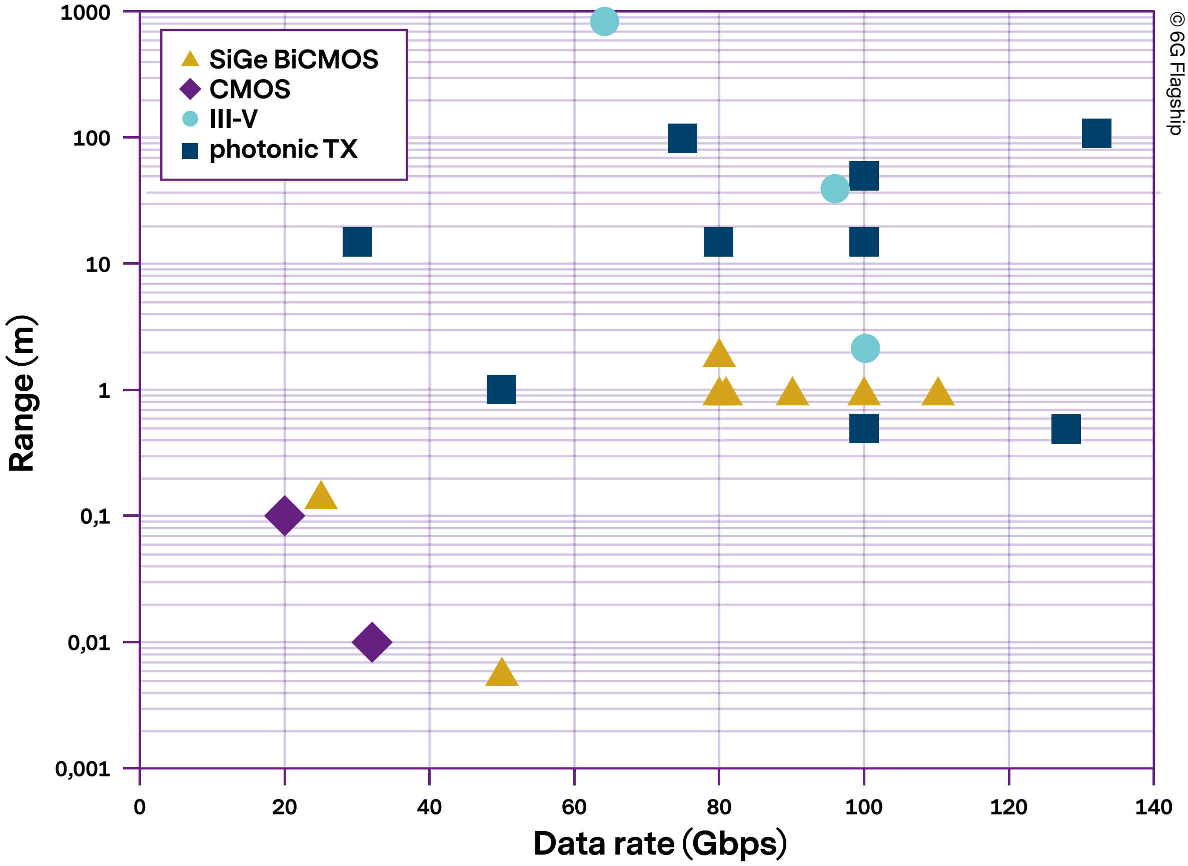
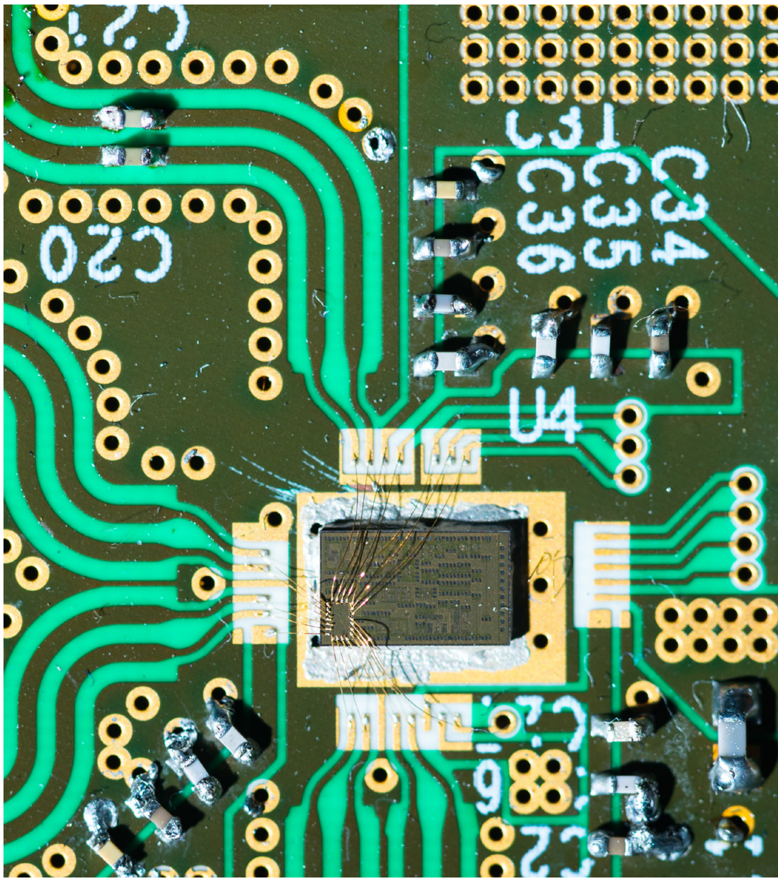
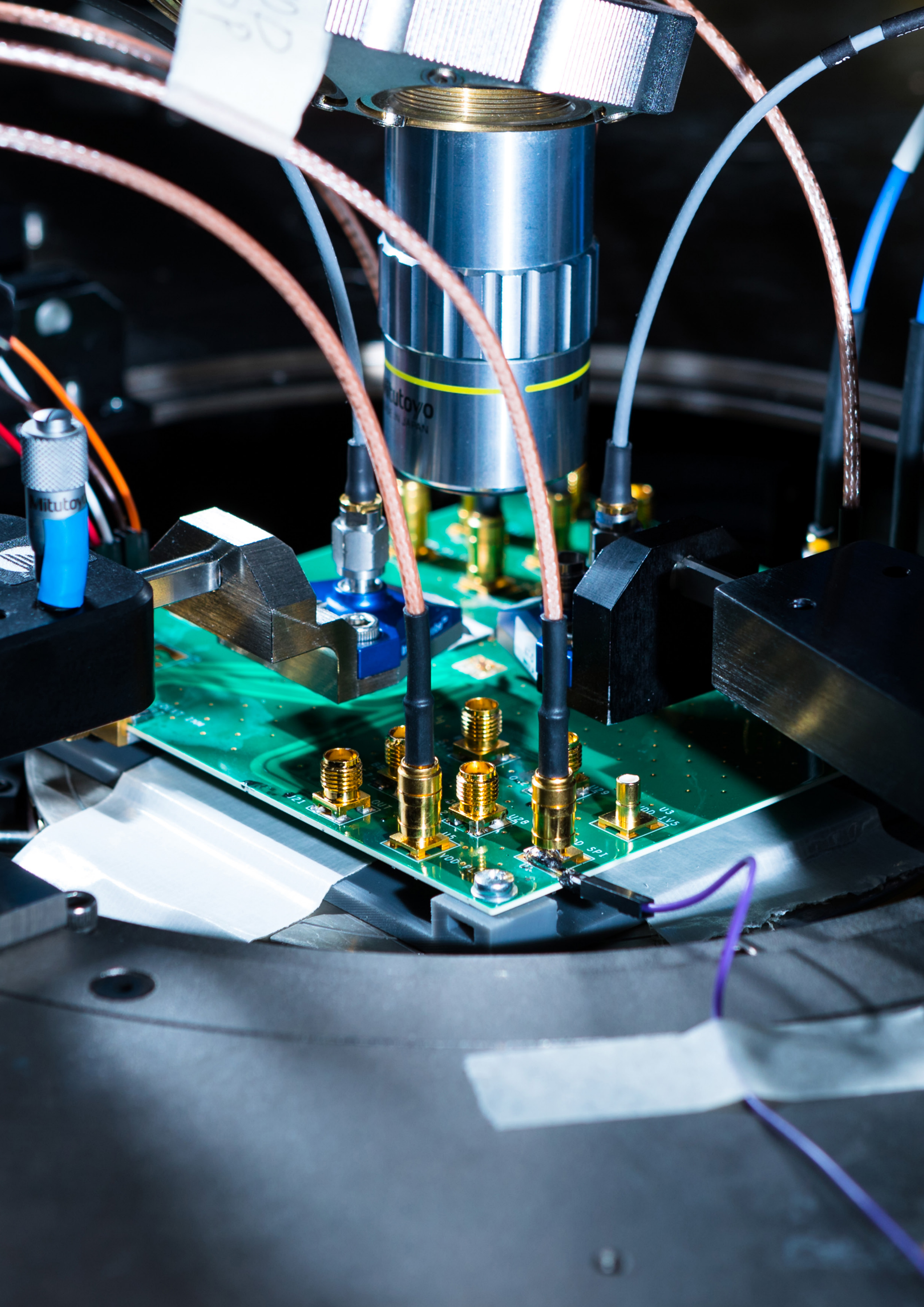


Figure 3.4. State-of-the-art very high-speed link trials.

[RZD20], [PTL21]. They are targeted at manipulating wavefronts beyond phased arrays and MIMO transceivers to improve the properties of radio channels for capacity and link range enhancements.

However, little is currently available to show the potential of many new techniques, although the need for something better exists. Verifying interesting theoretical concepts requires substantial time, and feasible implementation may not be obvious. These and other potential communications paradigms therefore typically take years before they can be adopted in commercial systems. Feasibility studies need serious prototyping with relevant technologies before their potential in the 6G context can be properly evaluated. Many of these challenges are related to the physics-based constraints of hardware technologies [GFF21]. The key aspects of 6G communications and sensing will be discussed in detail in the following chapters.

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Semiconductor technologies at the edge 4

Semiconductor technology developments have enabled the evolution of digital communication systems from 2G to 5G. It is obvious that advances in these technologies are needed when new requirements for 6G are the focus. However, the fast evolution of communication speed according to Edholm's law is challenging implementation at accelerated speed compared to the evolution of Moore's law. Although space does not permit a deeper analysis here, there are other sources, and some are quite critical in the discussion of the evolution of wireless communication with respect to digital technologies and their tradeoffs, including digital conversion [DFS20], [MA17].

We will focus here mostly on the fundamental challenges of radio frequency (RF) circuits in terms of power generation and noise. These are the first obstacles to be overcome when investigating the feasibility of extremely high-speed and high-bandwidth circuits. In recent decades, since the birth of 2G, the adopted carrier frequencies for dominant commercial applications like smartphones have moved up more slowly than the evolution of technologies would have allowed. However, evolution in RF, analog, and digital conversion is neither as fast nor as straightforward as Moore's law predicts for digital. Furthermore, as we are now adopting the lower mmW region in 5G first and targeting even the higher-frequency part of this region in 6G technology, the speed of the transistor is beginning to become the kind of bottleneck we have not seen for a long time. Achieving the next step in communication and other wireless applications will therefore require more emphasis from day one to understand technology dependent hardware limitations much better than the previous concepting and development of 3G/4G/5G systems, from research to standards and products.

There is no such thing as a free lunch: Conceptual solutions that would make 6G more hardware-friendly, and thus feasible, should be studied, from details of transistors and associated materials to transceivers, antennas, and packaging. Although we will discuss only selected details in this white paper, it is essential to understand that radio entails more than antennas or individual amplifiers. It is a complete system with various bottlenecks, including power, noise, linearity, signal conversion, and the generation of clean, high-quality RF and clock references, among many other things. Failure in any of these will prevent us from moving forward in 6G targets. Finally, fundamental physical constraints lie behind all these parameters. Achieving adequate performance with decent cost and reasonable energy consumption is difficult to achieve, model, or predict. Although we greatly like to simplify, the complexity requires an endless number of trials and prototypes from individual blocks that gradually evolve as parts of complete systems. This will also take time, just as it has over the last more than 20 years to conquer the lower mmW region to enable 5G.

This section scratches the surface and lists some key obstacles for how to adopt upper mmW bands or even THz frequencies for applications targeted not only at low-volume, highly specialized products but for the mass market. It is impossible to predict precisely when we will be there with commercial products, or whether photonics will reach the same target first, coming from higher frequencies well above 1 THz down to upper mmW bands. Although the focus in hardware discussions is on higher frequencies, this does not mean that the optical range will not be an attractive alternative, at least to complement radio communications and other applications. This will be discussed at the end of the white paper. Once we attempt to move upward in frequency, at the same time, the more widely used RF spectrum, including the lower mmW region of 5G, will need much focus on mature solutions, add complexity to improve system performance whenever it makes sense, and examine more power-efficient approaches. This will happen in parallel with research into 6G. A more revolutionary path will therefore take the benefit of the entire available and feasible spectrum to implement cost-effectively by the time 6G finally launches.

4.1 Semiconductor technologies for upper mmW circuits

The performance of upper mmW or THz circuits and systems is constrained by the performance of active devices (e.g. transistors) and passive elements. Fortunately, semiconductor technologies have made significant progress in the past two decades, and several commercial device technologies can support >100 GHz applications, including both silicon- [HGR19] and III-V-based semiconductors. An example of CMOS evolution is illustrated in Fig 4.1. One should note that the transistor's intrinsic gain has increased somewhat faster than its extrinsic gain. The former means that closely placed transistors, for example, in digital circuits, will greatly benefit from the increased gain, i.e. speed. However, in RF circuits, extrinsic gain matters more, because the amplifying transistor must typically be terminated with a resonator load that is located in much higher metal layers in the IC process to guarantee the best performance. The local interconnect from transistor to load is therefore lengthy on a relative scale, and losses associated with it deteriorate the performance in practice. This interconnect issue is one of the core reasons RF circuits cannot fully natively exploit the benefits of new technology generations, making the design even more difficult as the frequency increases. The discussion in this section will focus mainly on the speed of active devices. The speed of transistors is evaluated with two figures of merit frequencies: f_T; and f_{max}. These indicate the frequency at which the transistor current gain (f_T) and power gain (f_{max}) drop to a value of 1 (= 0 dB).

For an appropriate technology choice for upper mmW and THz applications, speed is not the only criterion. Many other parameters must be considered, such as cost and mixed-signal or digital integration capabilities, to name a few important aspects. A high integration capability for mmW communication––which usually relies on beamforming––becomes increasingly important, because the beamforming circuitry requires complex yet fast control that is to be realized with digital circuitry.

As a rule of thumb, the transistor f_T/f_{max} should be more than twice the operating frequency (i.e. the RF carrier frequency) to obtain decent gain and efficiency in amplifier design. Beyond that, we need to rely on harmonic generation due to non-linearities [SGH15],[JHA20], which are known to be much more lossy, leading to lower output

1st year of production	Technology generation
2004	90 nm
2006	65 nm
2008	45 nm
2010	32 nm
2012	22 nm
2014	14 nm
2017	10 nm
2018	7 nm

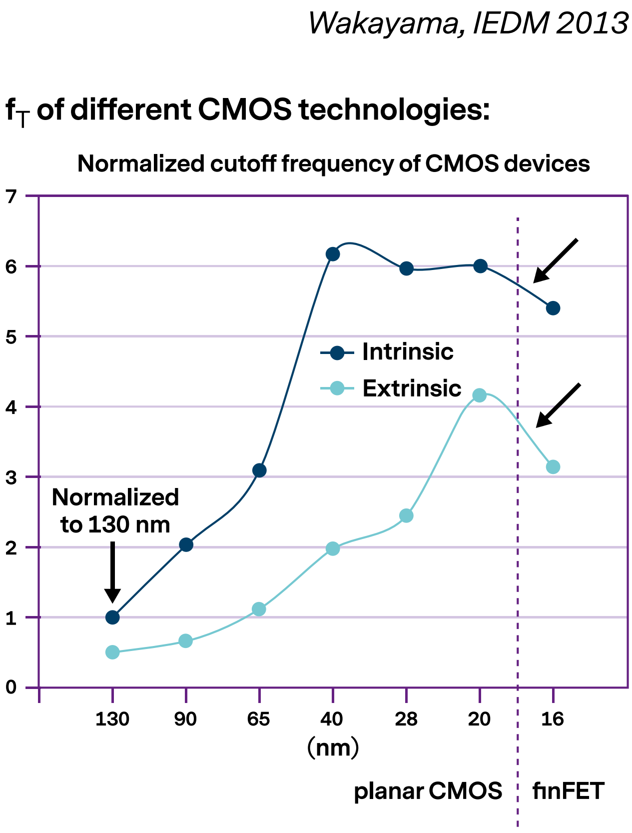

Figure 4.1: Evolution of CMOS downscaling: Technology generations and their year of introduction (left), and evolution of the cutoff frequency f_T with the different CMOS generations (right), based on [WAK13].

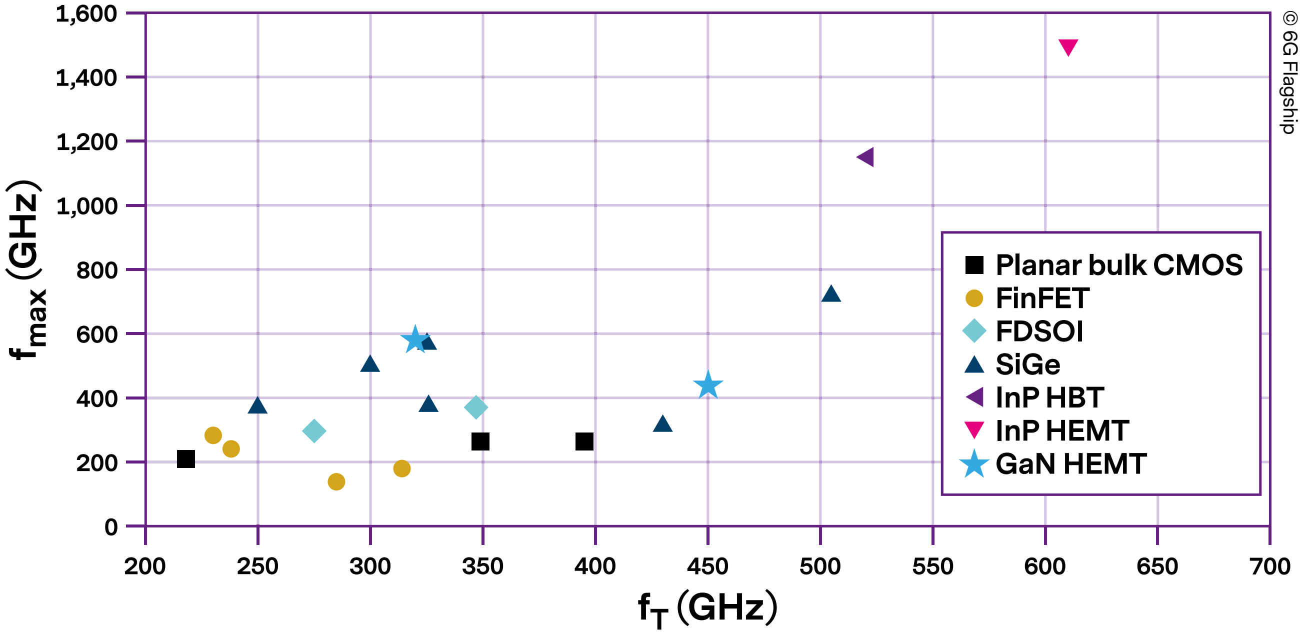

Figure 4.2 Overview of f_{max} and f_T of state-of-the-art semiconductor technologies.

power and higher noise [HGR19],[RGS18a]. Although there are already technologies that can achieve operation in the range of 100–1,000 GHz, the implementation of any larger system like an RF transceiver will be much more difficult than for 5G frequencies in the lower mmW region. One must remember that even at lower mmW frequencies, it is impossible to achieve similar performance to frequencies below 6 GHz with the same power consumption. The limitations arise from physics and the boundaries of different semiconductor technologies.

If we take a very simplified look at the fundamental boundaries of a wireless link budget, we can focus the discussion on the power generation capability of power amplifiers (PA) and the noise figure of low-noise amplifiers (LNA). These two provide the fundamental boundaries of the best possible link performance. However, in a full transceiver design, of course, further compromises need to be made, for example for linearity, signal combining, power consumption, spectral efficiency, and even form factor. Efficient power generation and low-noise amplification are further discussed in Sections 4.2 and 4.3.

Figure 4.2 compares the characteristics of transistor frequency cutoff, f_{max} and f_T. As the figure shows, the f_{max} of InP and GaAs transistors currently exceeds 1 THz. SiGe-based bipolar transistors have reached 700 GHz f_{max} [HRB16] and have good potential to extend this value beyond 1 THz band in the future. For CMOS and CMOS, SOI f_T and f_{max} saturate around 400 GHz. Further downscaling no longer brings an increase in speed, as discussed above.

RF GaN remains a research-oriented technology for >100 GHz applications. The wide bandgap of 3.3 eV is suitable for high-power, high-temperature applications, while delivering decent noise performance. While RF GaN is maturing at the time of writing for 5G base stations, attempts are also being made to downscale a GaN HEMT to shorter gate lengths, with an inevitable decrease in the maximum allowed supply voltage. A 20 nm GaN HEMT, grown on a SiC substrate, offers 454 GHz f_T with 444 GHz f_{max} [MBR16]. For increased integration and reduced cost, a GaN double-heterojunction HEMT might be grown on silicon wafers (GaN-on-Si) to leverage the scale of manufacturing techniques, and is currently an active research and development trend. The state-of-the-art GaN/Si devices already reach 300–400 GHz f_T/f_{max}, and the application of the GaN technology in 100–300 GHz systems should be seen within a few years. Nevertheless, the electron mobility in GaN is not higher than in silicon, meaning that for circuit operation well above 100 GHz, high-mobility III-V materials may be preferred.

Commercial gallium arsenide (GaAs), commonly available in high-electron-mobility transistor (HEMT) and heterojunction bipolar transistor (HBT) technologies, e.g. 100 nm pHEMT, supports MMICs up to the high W-band (<110 GHz).

Advanced indium phosphide (InP), used both in HEMTs and HBTs, is even faster and has better integration capabilities than GaAs with as many as 4–5 metal layers. In 2015, with a 25 nm HEMT device, a 1.5 THz f_{max} and an associated f_T of 0.61 THz were demonstrated. InP DHBTs (double-heterojunction bipolar transistors) lag only slightly behind, demonstrating 1.15 THz f_{max} and simultaneous 0.52 THz f_T at a 130 nm node. The breakdown voltage is 3.5 V: It thus has better power capabilities than its

HEMT counterpart. The downside with InP is its relatively high manufacturing cost and the modest integration of complex analog and digital functions. Like GaN, we expect research in the coming years to bring InP devices to a higher integration degree by co-integration with silicon and adding more metal layers. The superior speed capabilities can thus be better exploited and deployed at a large scale for 6G.

Owing to their cost and integration advantages compared to III-V compounds, Si-based technologies, CMOS, and **SiGe HBTs**, the latter preferably combined with CMOS in BiCMOS technologies, will play a major role in communication circuits for both the lower and upper mmW bands. With a SiGe BiCMOS process that is commercially available today, e.g. the B11HFC process from Infineon [DTL14], with f_{max} and f_T values of 435 GHz and 250 GHz respectively, one can design circuits and systems with good performance in the D band (around 150 GHz) [LHE14]. As a result of European effort and investment, the most advanced SiGe HBTs with peak f_T of 505 GHz and peak fmax of 720 GHz have been demonstrated at the research level. The industrialization of this technology, which results in a slightly lower f_{max} of around 600 GHz, is currently in its qualification phase, and a commercial release for engineering is anticipated in one to two years. Yet the breakdown voltage of these very high-speed silicon bipolar transistors is lower than for an InP HBT. As a result, the transmit power and efficiency of a PA with InP HBTs can be made higher than for the silicon bipolar counterpart [RGH19]. This is especially important in applications where the number of antenna elements must be minimized. On the other hand, with a large number of antennas, the required transmit power per PA can be reduced so that a lower PA efficiency is less detrimental to the efficiency of the beamforming transmitter.

The scaling of **CMOS** is essentially driven by logic applications for which area scaling and/gate delay are most relevant. Gate delay is more related to f_T than to f_{max}, so f_{max} does not actually follow the scaling as f_T does. Nevertheless, with f_T and f_{max} values reaching 400 GHz, it has become realistic to realize mmW circuits in CMOS, reaching the upper mmW frequency range already [FSA19]. In this reference, CMOS technologies with the best f_T/f_{max} for RF applications are based on silicon-on-insulator (SOI) which isolates the devices from the silicon substrate, as well as from each other. The isolation is not only important to enhance f_T/f_{max}, but is also a key for improving the performance of the on-chip passive elements. High-resistivity SOI further helps the design of high-quality on-chip passives.

Due to limited amplification capabilities, the early CMOS THz circuits are typically based on a harmonic generation or frequency multiplication technique [LHY19], [HGR19]. However, using harmonic power leads to relatively low output power and a high noise figure, limiting the communication distance. In another example, a recent paper using a subharmonic injection-locked triple-push method reported a 1x4 0.53 THz source array with -12 dBm output power in standard bulk Si CMOS (40 nm) [GZR19]. Nevertheless, power generation with CMOS is still inferior to what can be obtained with silicon HBT transistors in SiGe BiCMOS, e.g. packaged 1-THz Tx/Rx chip sets reported -37 dBm in 2015 [SGH15]. Single SiGe radiators deliver –6.3 dBm [HGM19], or even up to +10.3 dBm in an 8x8 array at 430 GHz [JHA20].

In summary, SiGe HBTs and even CMOS will play an important role as upper mmW range technologies at 100–300 GHz, although for some applications where high transmit power is required, one can consider the use of high-mobility III-V devices for the front-end if this can be done in an economically viable way. In applications between 300 GHz and 1 THz, these high-mobility devices will continue to be the key technology. With recent progress offering nearly 500 GHz f_{max}, GaN could become attractive for power amplifiers, thanks to its wide bandgap. Recent progress in GaN-on-Si will further leverage the acceptance of GaN in wireless communication, while similar progress for high-mobility materials like InP may give an additional boost to the THz range.

Power amplifiers and low-noise amplifiers play very specific roles in transmitter and receiver designs respectively. Their specific properties therefore determine the ultimate limits for the achievable link range with highly frequency-dependent power delivery and noise properties. The performance of PAs and LNAs depends strongly on the speed of the technology, as discussed earlier (f_{max}, f_T). They will therefore be discussed specifically against these tradeoffs in the following subsections. Naturally, the performance of a transceiver does not only depend on them, but it cannot improve either. Furthermore, RF transceiver power consumption in phased arrays at high frequencies is no longer dominated in a similar way by the efficiency of the PA to radios operating below 6 GHz. One must optimize architecture and energy efficiency in RF for broadband signals taking the whole transceiver, including data converters (ADCs and DACs), into account. This is discussed in the subsection about mixed-signal circuits (i.e. ADCs and DACs) at the end of this chapter.

4.2 Efficient power generation above 100 GHz

Frequency bands above 100 GHz offer opportunities for reducing phased array antenna size, while supporting high data rates or high-resolution imaging. However, high output power is required from each element to overcome path loss, and the high power in reduced half-wavelength array spacing increases power density demands. Higher frequency bands increase free-space path loss per antenna element, but a similar link gain is realized with fixed aperture size relative to lower frequency bands, as stated previously. Furthermore, the reduced wavelength supports finer angular resolution for beamformers and multiple-input/multiple-output (MIMO) schemes. A key metric for the development and adoption of integrated circuit technologies in these bands is the ability to 1) develop enough power at these bands and 2) achieve reasonable efficiency through the entire transmit chain.

Figure 4.3 plots the RF output power per element for a fixed EIRP (effective isotropic radiated power) in a phased array beamformer for a notional base station and handset application. This is essentially the power toward the main lobe direction of the beam. As the number of elements increases, the output power per element reduces. However, the complexity and size of the array increase, posing additional challenges for integration. In a handset, a 45 dBm EIRP is required. If this is realized with a 16-element antenna array, an average output power of around 16–20 dBm per PA is needed. With more antennas, the required average power per PA decreases at the expense of a larger form factor: A doubling of the number of antennas reduces the required transmit power per PA with 6 dB. On the other hand, in a base station, a 75 dBm EIRP might be demanded. Then an array of 256 elements requires 25 dBm-27 dBm output power of each PA.

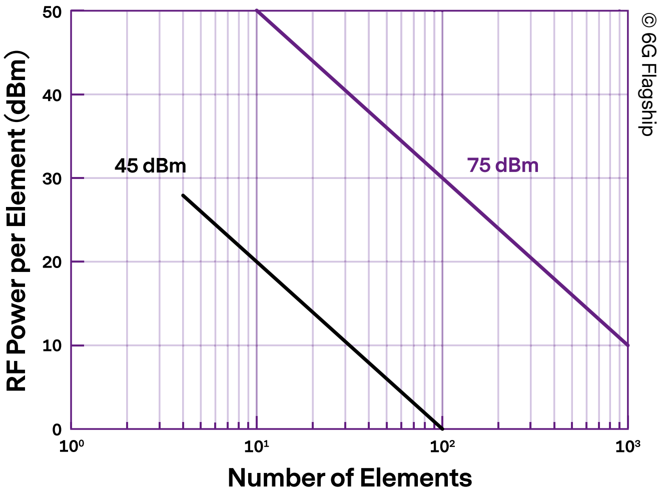

Figure 4.3. EIRP targets for the handset (45 dBm) and the base station (75 dBm) for a >100 GHz transmitter.

We can map these requirements to the process technologies that will support a radio architecture, as shown in Figure 4.4. While ultra-scaled CMOS can be leveraged for the digital signal processing and mixed-signal components, RF CMOS technologies, including SOI CMOS, offer the scale to integrate upconverter and downconverter components. Nonetheless, these technologies are limited in power generation and efficiency above 140 GHz. Consequently, III-V semiconductors such as InP, GaN, or GaAs might become necessary for high-efficiency and high-power power amplifiers (PAs) and low-noise amplifiers (LNAs). However, the power levels in excess of 8 dBm at frequencies around 220-250 GHz have been recently demonstrated for SiGe BiCMOS technology nodes without any power combining techniques [RGH19], [RGH20].

Projecting the capability of III-V and CMOS for power and efficiency suggests a partition of power generation in the architecture. With III-V PA technologies that achieve more than 30% power-added efficiency (PAE or η_{PA}) for PAs, the complete transmitter (TX) can operate with a DC-to-RF efficiency of 10%, including the TX circuitry. The TX efficiency (η_{TX}) is approximated from $1/\eta_{TX} = 1/(G_{PA} \cdot \eta_{MOD})$. With a high PA gain (GPA), the modulator efficiency (η_{MOD}) becomes less significant. However, the low maximum available gain of device technologies above 100 GHz suggests that PA gain is limited, typically less than 10 dB per stage, and the modulator efficiency places constraints on the overall PAE. Higher PA gain is possible with additional gain stages. The limited area in linear or 2D arrays places severe constraints on the additional PA area required for multiple stages with a higher gain. Since the dimensions of a unit cell are bounded by half the wavelength, the area scales based on the required area for silicon-based upconverter/downconverter, and

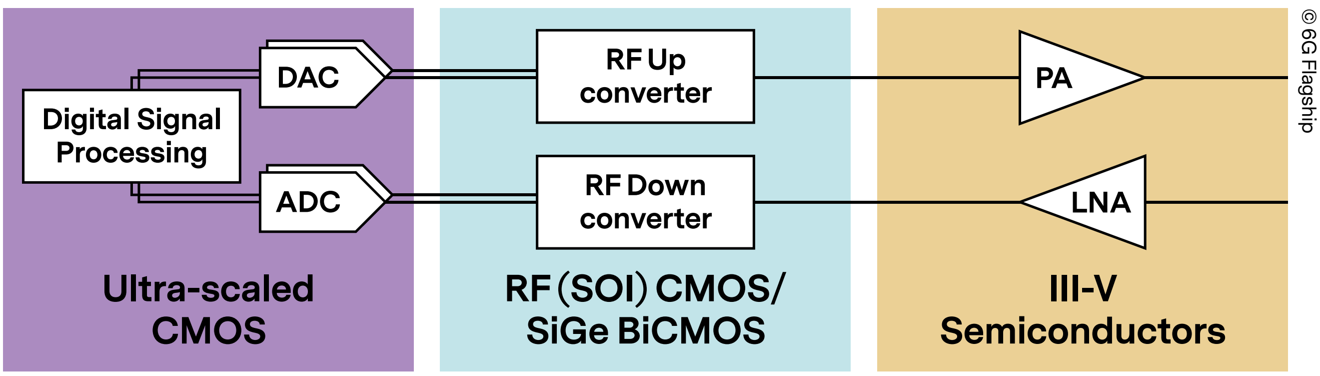

Figure 4.4. Technology mapping to architecture for upper millimeter-wave/terahertz systems. RF Upconverter should be named as RF modulator.

the area of each PA stage, assuming that both ICs must fit within the linear or 2D grid dimensions. Linear scaling in the PA area assumes that passive matching networks, rather than transistor area, dominate the amplifier stage area. Area demands tend to limit the available PA area for multistage designs. Consequently, optimization and co-design between the PA and upconverter are important considerations for designing and packaging efficient transmitters above 100 GHz.

4.3 Power amplifier technologies

Prior work based on SiGe, InP, GaN, and CMOS have shown that multiple device technologies are capable of producing more than 17 dBm above 100 GHz, but the efficiencies of power amplifiers (PAs) are generally under 10% [DB18], [GUR19], [CSB18], [SR18], [RGH19], [RGH20]. Of the recent demonstrations, InP HBTs have offered the best tradeoffs in high power, high efficiency, and power density at 140 GHz [GUR19]. A relatively mature InP 0.25um process offers f_{max} of 600 GHz, with a breakdown voltage of 4.5 V, for high efficiency with moderate output power at 140 GHz. An investigation of HBT amplifiers suggests that common-base amplifiers have a maximum available gain (MAG) of roughly 16 dB at 140 GHz, as opposed to the 10 dB MAG of the common-emitter amplifier. Higher gain translates to higher efficiency at 140 GHz. A pseudo-differential PA architecture leverages a sub-quarter-wavelength balun to provide input/output single-ended to differential conversion [DB18]. With class B biasing, the pseudo-differential PA can reach peak efficiency exceeding 30% at 140 GHz while providing more than 17 dBm output power [NFR20]. Multistage PAs provide more than 20 dB of gain with efficiency of 25% [ASF20].

Gallium Nitride (GaN) HEMT technologies have also been scaling toward applications above 100 GHz. Advanced 90-nm GaN processes offer f_{max} of approximately 320 GHz and provide for a MAG of roughly 8 dB. A recent 120-GHz PA demonstrated output power exceeding 25 dBm, while the peak efficiency was 16% [CBL19].

To evaluate different semiconductor technologies and their power generation capabilities, a survey undertaken by a research group at Georgia Tech gives a highly illustrative view of PAs published in major conferences and journals since 2000 [WWL20]. It is clear that power generation capability will start to degrade drastically above 100 GHz, because the f_{max} of the transistor starts to be a major bottleneck for performance. Figure 4.5 shows the saturated output power of a PA as a function of the operating frequency for CMOS and InP. Clearly, InP is superior to CMOS here. Other technologies have not been shown in order not to overload the figure. The performance with SiGe BiCMOS for operating frequencies beyond 100 GHz is between the CMOS and InP performance.

4.4 Low-noise amplifiers

While power delivery capability is extremely important for a decent link range, noise dominates receiver sensitivity to detect small signals at the other end. Any degradation in the noise figure directly impacts the range. As with the limitations to power delivery capabilities and gain by transistor technology, as discussed in the previous section, the noise figure (NF) of a low-noise amplifier (LNA) is mainly limited by the noise performance of a transistor, which is found to be proportional to the ratio of the operating frequency and the f_T of the technology

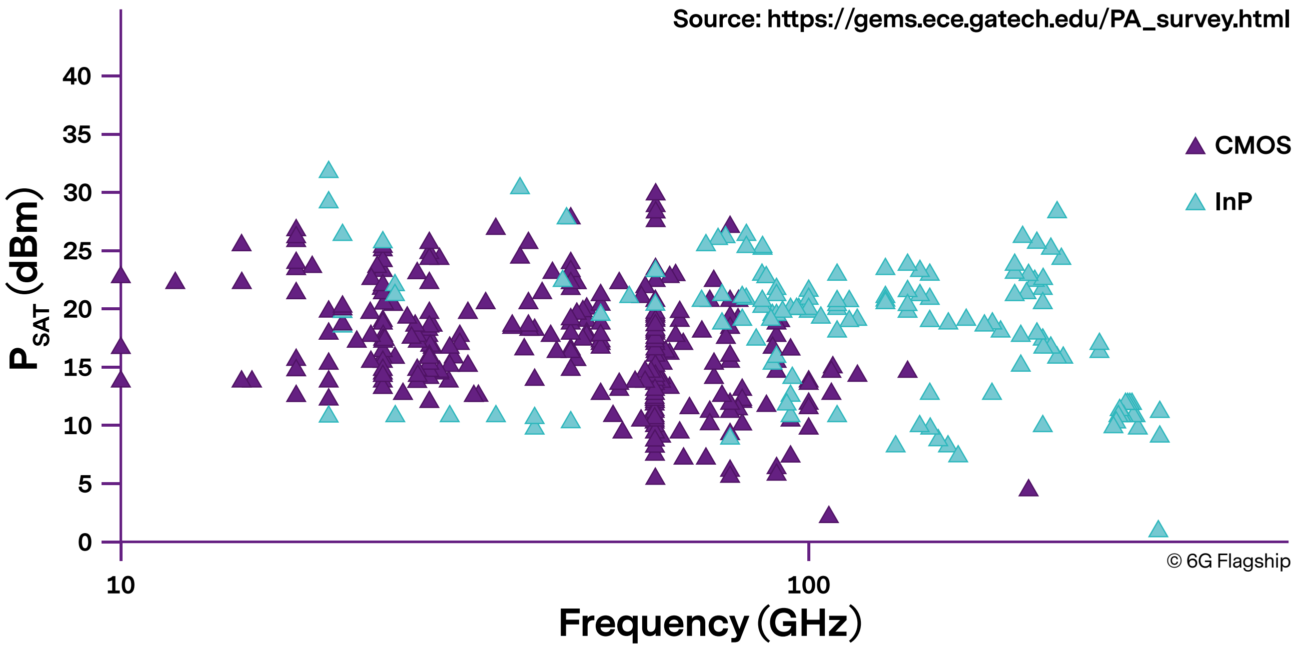

Figure 4.5. Output power vs. operating frequency of PAs according to [WWL20].

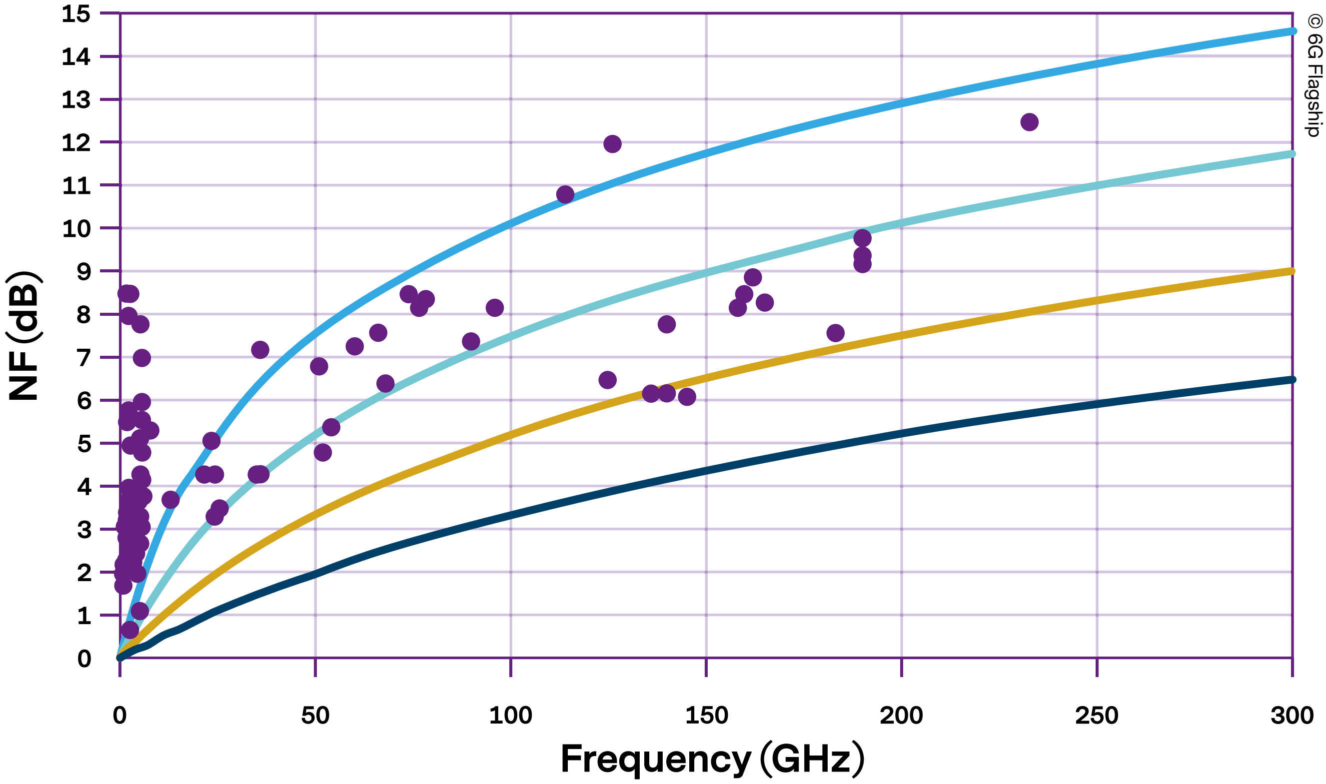

Figure 4.6. Noise figure of recently published multi- and wideband LNAs, using SiGe and CMOS technologies.

[MAT18]. In a practical LNA design, the noise figure cannot be as low as the minimum noise figure of one transistor, because other noise sources are also present in the LNA. If we examine some recent LNA implementations from the GHz range up to more than 200 GHz [AL20], [PVK18], [AHK18], [RGS18], [SGS16], the trend is evident, according to Figure 4.6. Four trend lines are drawn, presenting the theoretical increase of noise as a function of frequency. Each trend line presents a different f_T if other scaling parameters are assumed to remain the same, and the curves are drawn such that they represent very significant 2x improvement between the speed of technologies. One could see that moving from 28 GHz to 280 GHz in communications can easily lead to more than 5 dB degradation in the NF of a single-stage amplifier, strengthened by the fact that the lower gain of that stage will result in a higher contribution of noise from the subsequent stages. Due to this, noise performance limited by semiconductor physics is also a major factor, limiting link distance as we move up in frequency.

4.5 Mixed-signal transceiver circuits

Next to the RF circuits, a communication system contains analog and digital baseband circuits. The implementation technology for digital functionality will continue to follow the CMOS scaling route, which is justified by the expected large market volumes of the radio chips. CMOS scaling has made the transition from the planar bulk CMOS device to a FinFET, while for generations beyond 5 nm, gate-all-around devices or nanosheets may take over. In addition, scaling boosters as special process or layout constructs such as super vias and buried power rails will be considered to continue area reduction, while being increasingly confronted with limitations in patterning and electrical device performance [MWD18].

Some key analog building blocks are present on these digital chips. The data converters that do the conversion between the analog and the digital domain are the most important in the context of communication. With the increase of data rates, the design of analog-to-digital converters (ADC) is more critical than the digital-to-analog converters (DAC). This section therefore focuses mainly on the ADC which, in the receive chain of a wireless communication transceiver, transforms the received signal after downconversion from mm-wave frequencies down to baseband frequencies to the digital domain.

The data rates up to 100 Gbps that are expected to be realized for 6G require an unprecedentedly wide RF bandwidth. Classical receiver architectures bring the RF signal down to the baseband, such that the baseband bandwidth is half the RF bandwidth. Converting this analog baseband signal to the digital domain without aliasing requires a sampling clock frequency that is at least twice the analog baseband bandwidth. As a concrete example, we assume a 100 Gbps data rate with a 64-QAM modulation scheme. This modulation has a spectral efficiency of 6 bit/s/Hz. Subtracting 1 bit for this coding yields an effective spectral efficiency of 5 bit/s/Hz, necessitating an RF bandwidth of 20 GHz, and hence a minimum sampling rate of 20 GHz for the ADC. For 64 QAM, the effective number of bits should be such that the signal-to-noise ratio (SNR) limitation caused by the quantization is at least 10 dB higher than the required SNR for the given modulation scheme. Taking an SNR around 23 dB for 64 QAM with a 5/6 code rate leads to 6 effective bits. In addition to the SNR requirement, extra bits need to be provided to faithfully digitize peaks in the analog signal. For 64-QAM modulation, the ratio between the signal peaks and the average value is more than 6 dB, such that at least one more bit is needed for the ADC. In addition, the strength of the ADC input signal is not always constant, in spite of the use of a variable-gain amplifier in front of the ADC. To cope with these two requirements, a resolution around 8 bits will be needed in combination with sample rates beyond 10 GHz. This poses a challenge for the power consumption of the ADC.

High-speed ADCs with medium resolution are nowadays mostly realized with interleaved architectures that use sub-ADCs realized with an SAR (successive approximation register) or pipeline architecture. It is expected that this approach, with even more extensive interleaving, will be followed in 6G. As mentioned above, ADCs often reside on the same chip as the digital modem, and the implementation technology will therefore still follow the scaling evolution of CMOS. The analog performance (like flicker (i.e. 1/f) noise, matching) of advanced CMOS technologies will be a focus. On the other hand, increasingly complex background and foreground calibration techniques will be used in ADCs to compensate for the analog impairments.

To get an idea of the performance and power consumption that can be obtained as of today, Figure 4.7 shows the Walden figure-of-merit FOM_W as a function of speed for a large set of published ADCs, as maintained in the survey of [MUR20]. This FOM_W is defined as

$$FOM_W = \frac{P}{2^{ENOB} \times f_s},$$

in which P is the power dissipation, ENOB is the effective number of bits, and *fs* is the sampling rate. From the graph in Figure 4.7, one can estimate the expected power consumption. For the specifications mentioned above, the power consumption levels are above 100 mW.

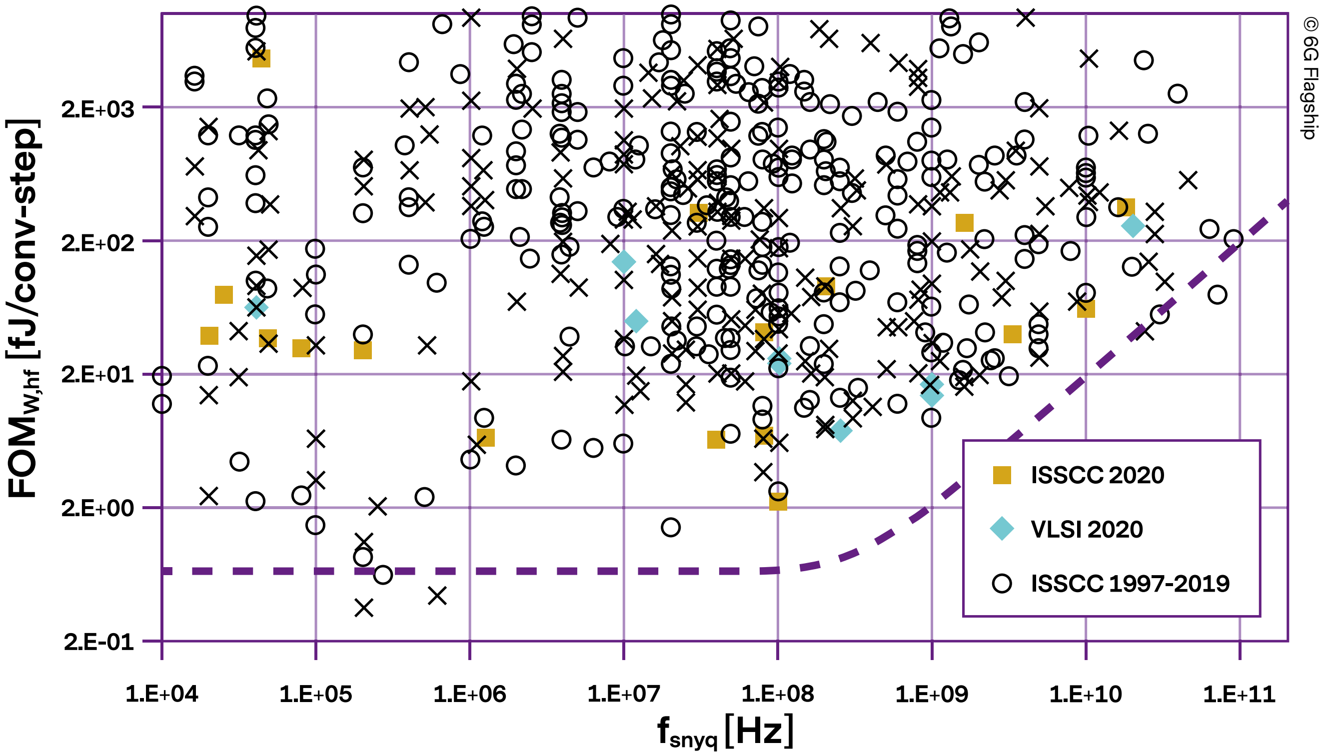

Figure 4.7: Scatter plot of the Walden FOM of published ADC design versus speed [MUR20].


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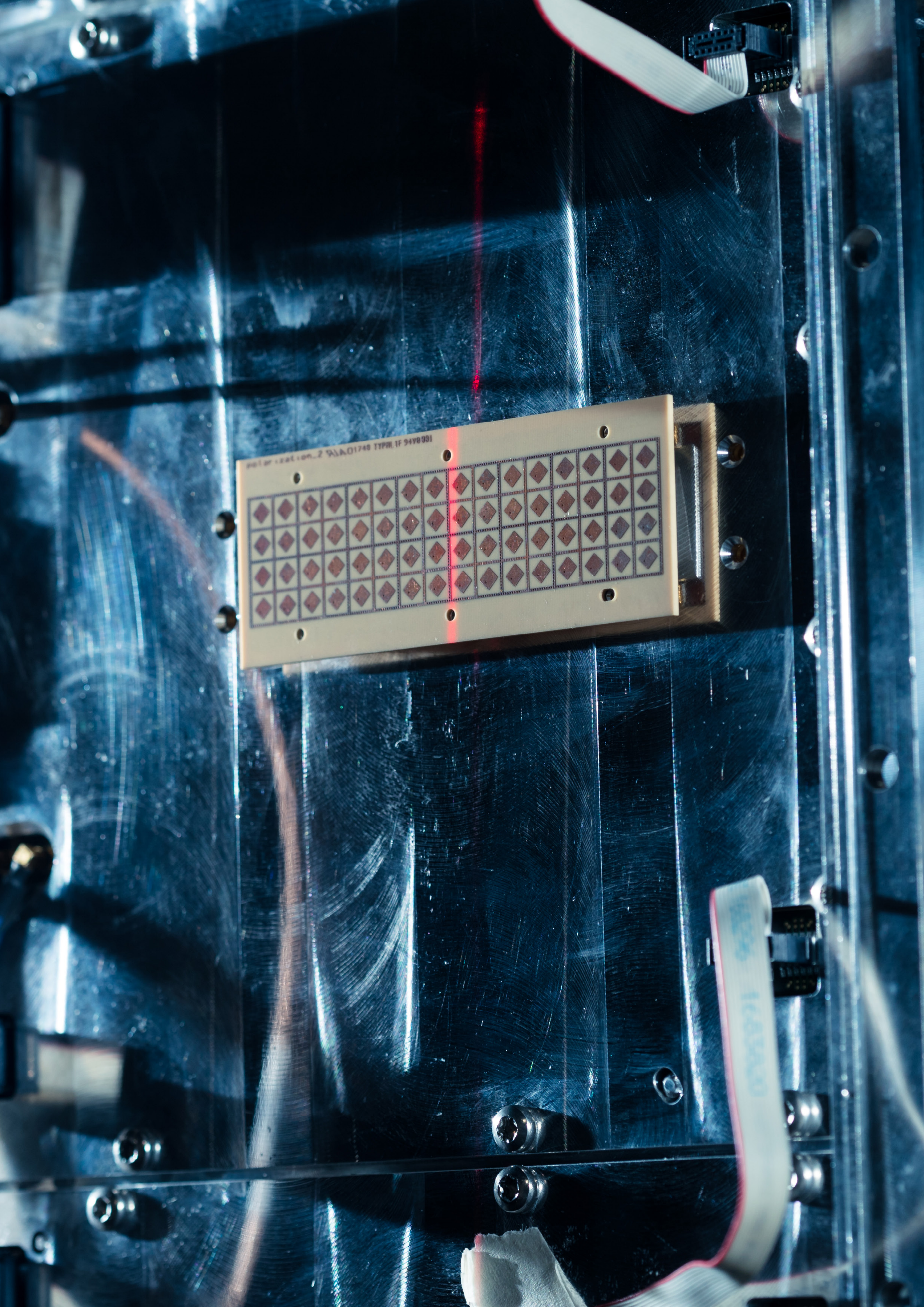

polarization_2

New forms of antennas and packaging

5

This chapter discusses the packaging of only the communication hardware. Packaging aspects related to other functions such as cameras in a smartphone are not discussed here. Furthermore, the packaging of the complex digital signal processing and memory functions is expected to be an evolution of the 5G approaches toward higher complexities. In this chapter, we treat packaging aspects of the analog front-end and transceiver with the connection to the antenna.

Traditionally, the analog parts of a wireless communication system, consisting of a transceiver, several front-end modules, and antennas, are all designed separately, and they are placed in a 2D fashion on a carrier like a printed circuit board (PCB). This will no longer be feasible for 6G due to the significant interconnect losses above 100 GHz. Antennas at sub-THz will need to be tightly integrated with the packaging, RF circuits, and systems [RGH19],[RGH20]. Antenna-in-Package (AiP) technologies [CLN16],[ZM19],[LPG09] will be employed, as explained below, although on-chip integration of antenna elements, still challenging, may show an underestimated benefit in terms of considerably reduced packaging costs for terahertz-signal escape [RGH19]. As an alternative to a fully electrical implementation of a communication transceiver, THz range carrier signals can be directly converted to optical signals in stages: The signal from the antenna is first electrically amplified and converted to the baseband, and then again electrically amplified and converted onto an optical carrier by an electro-optic modulator [SHH15], [LAC18]. Of course, this mixed electronic-optical approach posits different specifications to the packaging compared to a fully electronic implementation.

6G communication systems will––just like the mm-wave part of 5G––make use of antenna arrays such that the beamforming array gain can compensate for the high free-space path loss. The small wavelength allows the use of more compact antennas and hence a larger number of antennas than for 5G, which can lead to a very high EIRP. The maximum allowed EIRP is typically limited by regulations (see also Chapter 3). To avoid grating lobes, the pitch of the antenna elements needs to be a half wavelength in free space (λ/2). The number of antennas and chips will depend on the required link length, EIRP, noise figure, power dissipation, cost, and form factor. For example, in base stations, highly integrated ultra-Massive MIMO (uM-MIMO) in 6G will employ thousands of antenna elements to significantly increase the capacity. On the other hand, in mobile 6G user equipment, form factor limitations will inevitably result in much smaller antenna arrays. However, to avoid blockage when using a mobile device, arrays will be duplicated over several places in the device [DKO18].

The limited capabilities of CMOS to generate much output power above 100 GHz will necessitate the use of non-CMOS technologies (SiGe BiCMOS or III-V) for many applications. Only for very short-range applications that are not dominated by the power consumption of the power amplifier (PA) can the transceiver functionality be combined with front-end circuits (PA and LNA). Most of the application cases will require a combination of one or more transceiver chips (which will probably be implemented in CMOS) with (non-CMOS) front-end chips and an antenna array. Combining these different chips is more challenging for the packaging than if one single IC technology covered all the active circuitry.

The number of antennas in an antenna array will mostly be too big for a linear placement with an acceptable aspect ratio. Instead, a rectangular or square array will be used. The implementation of the beamforming electronics strongly influences the interconnections between chips: realizing this functionality on the transceiver chip requires many connections (one connection per antenna path) to the front-end, which then consists of PA and

LNA only. Conversely, the number of connections between the transceiver and the front-end is much smaller when the latter also contains beamforming functionality that comprises a split of signals (in TX) and combination of signals (in RX). In addition, packaging technology can be used to realize the passive components needed in beamforming or front-end circuitry. For example, Wilkinson splitters/combiners, IQ hybrids, and baluns can be realized with lower losses than their on-chip counterparts and may be an alternative if extra chip-package transitions are avoided, which could again yield extra loss or constrain bandwidth. Hence, optimal architecture requires a detailed analysis of semiconductor technologies and packaging options, including substrates and their associated interconnects.

A possible packaging approach to housing the active circuits and the antenna array with a minimum interconnection distance is a vertical stack: chips and antennas placed on top of each other. This also has the greatest potential to limit the footprint as much as possible. Such a stack is practical if the pitch of the front-end circuits, which is determined by the size of the PA and LNA, can be kept smaller than or equal to the λ/2 antenna pitch. While this is not a problem for the lower mm-wave frequencies in 5G, this constraint may be violated at upper mmW and THz frequencies, because the pitch of the front-end circuitry on the IC does not decrease as quickly as the antenna pitch when the frequency increases [SGV19]. An important limiting factor for front-end pitch reduction is the large size of the bond pads, which is in turn often dictated by the pitch of the off-chip interconnect on the carrier material. PCB technologies or packaging technologies that feature an interconnection pitch well below 100 µm are needed to reduce front-end chip size. If front-end and antenna pitches differ too greatly, the use of dummy antenna elements can be considered, but this comes at the expense of sidelobes in the radiation pattern.

The choice of materials for an AiP approach depends on different criteria. The electrical performance of transmission lines depends on the permittivity (Dk) and loss tangent (Df) of the substrate. Moreover, warpage prevention should be verified. Thermal conductivity and thermal stress are also important due to the expected high-power dissipation, especially in the transmit part.

For the transition from the chip to the carrier substrate, bond wires should be replaced by stud bumps, microbumps or flip-chip solder bumps, because these have smaller (electrical) parasitics with good reproducibility. However, care must be taken not to constrain the signal bandwidth with the residual parasitics. Here, embedded die packaging techniques can be considered for a further reduction of these parasitics.

For the packaging of electronic systems, as an alternative to PCB(-like) technologies, 3D wafer-level packaging can be used to combine the front-ends with the antenna array and/or with the transceiver chip(s). For a vertical stack of the transceiver and front-ends, the size mismatch between the two parts determines the fan-out or fan-in layers between them, influencing the choice between a wafer-to-wafer, die-to-wafer, or die-to-die packaging approach. In addition, wafer-integrated optical interconnections are promising technologies for wide-band and large-capacity data communications. Silicon photonics has the advantages of compact device integration on a chip, and is low-cost, with high-speed and large-capacity performance [MHK16].

Exploiting the third dimension to limit footprint and/or interconnection length entails the use of through-substrate vias through the package dielectric or mold material. A further step would be the use of through-silicon via (TSV) contacts in a chip. TSVs today are not standard in RF/mm-wave chips. However, this may change, in line with an evolution seen in memory and logic: as the area downscaling of CMOS devices slows, the use of the third dimension is becoming an appropriate method for a reduction of the footprint of the IC in general, making TSVs in chips more standard (despite the extra cost). This can also be exploited in mm-wave circuits to reduce the footprint or provide paths for spreading the dissipated heat. Heat evacuation will indeed be a challenge when the volume of a package that contains complex electronics and antenna arrays is minimized. Furthermore, the efficiency of transmitters operating above 100 GHz is expected to be lower than for 5G frequencies, such that more power is dissipated for the same transmit power. Also here, the third dimension should be exploited to include heat-spreading planes, TSVs as thermal vias, or in extreme cases, liquid-based jet impingement [TOC17].

If form factor constraints can be relaxed, or if more volume is required for sufficient heat dissipation, the transceiver and front-end circuits and antenna array can be put next to each other, using a 2.5 D interposer or high-frequency PCB technology. However, if distances between chips or antennas increase, the reduction of interconnect losses is essential. At frequencies above 100 GHz, the availability of transmission lines (TLs), waveguides, and other passive components that can be regarded as nearly lossless cannot be taken for granted. The quality factor (inversely proportional to the per-wavelength attenuation) of a TL usually increases as a function of frequency, but it saturates above 100 GHz. Yet TL losses on the PCB or interposer are much lower than on the chip. Whereas a very rough estimate at 100 GHz for the loss of on-chip TLs is 1 dB/mm, PCB technology achieves around 3 dB/cm, and metallic waveguides obtain 0.3 dB/cm. A further reduction of losses can be obtained by introducing air cavities in the dielectric layers of the TL. Power combining/splitting and/or routing involving different lengths in different paths can result in large power imbalances, in addition to phase shifts. An alternative interconnect technology to bridge long distances is the use of fully dielectric waveguides made from low-cost polymers. These can be integrated with low-cost laminate build-ups, using standard flex-rigid PCB technologies.

As an alternative to the AiP approach, one could question if a 6G communication system with many antennas could also be built with multiple chips that each contain on-chip antennas in the same semiconducting substrate as the active circuitry on the chip. The advantage of this Antenna-on-Chip (AoC) approach [HGR19],[GAJ19] is that high-frequency transitions between a chip and a carrier substrate are avoided. Designing antennas within the constraints of e.g. bulk silicon CMOS, with its low resistivity substrate and stringent metal fill rules is challenging, but certainly achievable above 100 GHz [VVS19] and even beyond 1THz [GAJ19]. However, one should avoid substrate waves in the volume of the die degrading antenna efficiency. Moreover, the antenna efficiency is constrained by various aspects of the IC technology: the semiconducting nature of the IC substrate; the substrate thickness; the limited thickness of on-chip metallization layers; the need for dummy structures in IC technologies with copper metallization; … Next, the inevitable juxtaposition of circuits and antennas on the chip will probably lead to an antenna pitch larger than $\lambda/2$, which degrades the antenna pattern quality, as mentioned above. These complications and the area cost of on-chip antennas may limit the usage of on-chip antennas to small and preferably linear arrays.

Patches are most widely used for the antenna elements of a large array. For large bandwidths, a stack of multiple patches can be considered. In general, the use of metals for radiating structures beyond 100 GHz should be avoided as much as possible, due to the skin effect. Furthermore, the use of dual-polarized antennas offers the possibility of increasing capacity or avoiding a transmit/receive antenna switch by using a different polarization for the transmit and receive path. As 6G will need to coexist with 2G, 3G, 4G, and 5G, one could consider ultra-wideband or multi-band antennas and arrays to cover a wide frequency range, from 2G to 6G. Moreover, to influence the antenna radiation pattern, the use of metamaterials, electromagnetic bandgap structures, or artificial magnetic conductors can be considered. In the same vein, tunable metamaterials could play an important role for beam scanning without front-end phase shifters. Instead of always considering planar antenna arrays, the realization of antennas with either 3D printing or molding of (composite) dielectric materials in three-dimensional shapes (e.g. dielectric resonator antennas [FUM16]) is an important area of research into high-performance antenna systems for 6G. The reproducibility and cost of high volumes are important criteria for the feasibility of such technologies.

To give an idea of a package that combines an antenna array with front-end chips, Figure 5.1 shows a top, back, and end-fire antenna array topology. As this figure illustrates, a lens can be used to increase array gain [AAK16], [GSR18]. However, this comes with a reduction of the scan angle, which can be accepted for a fixed transceiver position (point-to-point links, backhaul, fixed wireless access, …). Further research is required into a new ultra-wideband silicon lens-coupled antenna system that will allow the

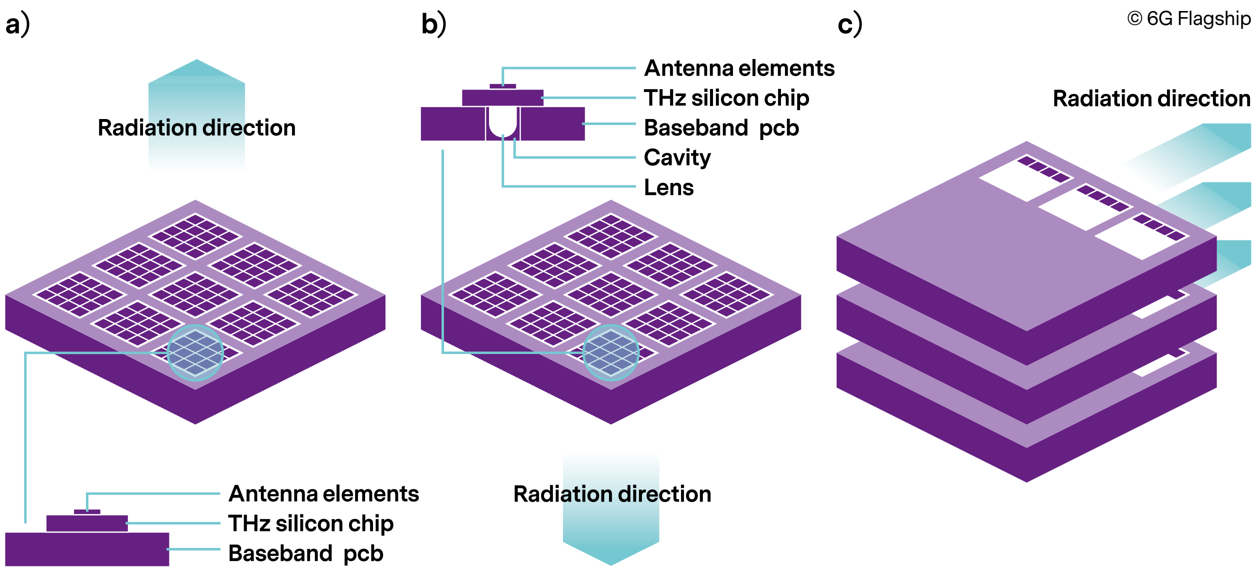
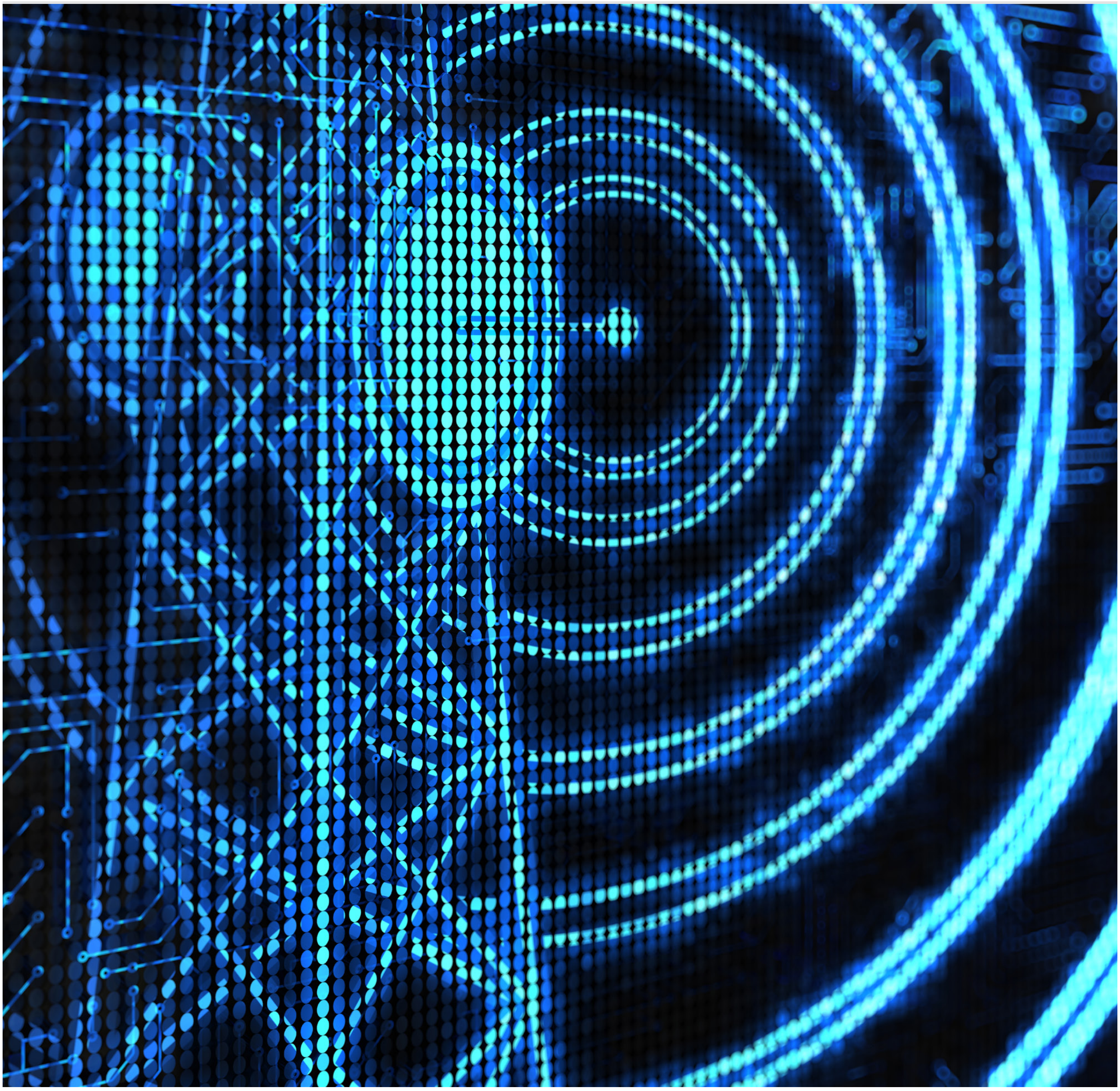


Figure 5.1. Phased array antenna topologies combined with ICs in a package for THz frequencies. a) nine radio pieces of 4x4 radiating element antennas with top radiated beam direction, b) nine radios of 4x4 radiating element antennas with back radiated beam direction, and c) end-fire antenna array topology with side radiated beam direction.



efficient coupling of THz radiation to the intrinsic device, without classical matching structures [GAJ19].

Nanotechnology opens new perspectives for THz communication to design and manufacture nanoscale electronic devices and systems in the terahertz range. Graphennas, i.e. graphene-based plasmonic nano-antennas, provide a technology to radiate electromagnetic waves with competitive conductivity over 100 GHz frequencies [ELA16]. Different kinds of metasurface can be added as part of the antenna structure for improving the antenna gain, isolation, reflectivity, or other properties. However, metastructures show characteristics that are similar to "plasmonic" structures. Along with graphene material, other 2D material, such as hexagonal boron nitride (h-BN), transition metal dichalcogenides (TMDs), silicene and phosphorene, can provide unique opportunities for future passive (antennas) and active (switches, transistors) electronic THz devices via properties such as adjustable band gap characteristics, ultrahigh carrier mobilities, and other ordinary mechanical and chemical properties [WY18].

In conclusion, 6G systems are complex heterogeneous systems that contain multiple chips, realized in different technologies, that are connected to an antenna array whose size can vary from tens to many hundreds of antenna elements. No single package solution is likely to serve all 6G purposes, but the third dimension will be exploited more than before to limit both interconnect lengths and footprint. The Antenna-in-Package (AiP) approach will be widely adopted. Moreover, many combinations of the technologies enumerated above can be made for the different solutions that need to be developed for different ranges, power levels, sizes, and so on.

Radio channel: is it different in 6G?

6

The transmission of electromagnetic (EM) waves is the basis of wireless communication and other radio applications. Transmitter and receiver antennas, with the propagation channel, constitute the radio channel. The characterization and modeling of the radio channel is essential in designing the capabilities of new wireless systems and evaluating the performance of system components. At frequencies below 6 GHz, channels have been well investigated and modeled for mobile communications. Lower mm-wave bands (<100 GHz) have also been measured and researched extensively during the last eight years for 5G studies, though there are still many knowledge gaps due to limited measurement capabilities. Currently, there is increasing channel characterization activity toward upper mm-wave (100–300 GHz) and terahertz (0.3–3 THz) bands. However, these high frequencies have been under research and utilization for decades for purposes other than communication, such as radar.

6.1 Some physics and facts about propagation

The Friis transmission formula indicates that doubling the frequency quadruples the free-space path loss. However, the EM field intensity at a certain distance is not a function of frequency (in a vacuum). Indeed, increased frequency will lead to a smaller antenna element that decreases the aperture from which the field is captured. Therefore, a constant antenna aperture over frequencies implemented with antenna array, for example, will omit the impact of increased free-space loss per individual antenna element (e.g. a dipole or patch). Another aspect

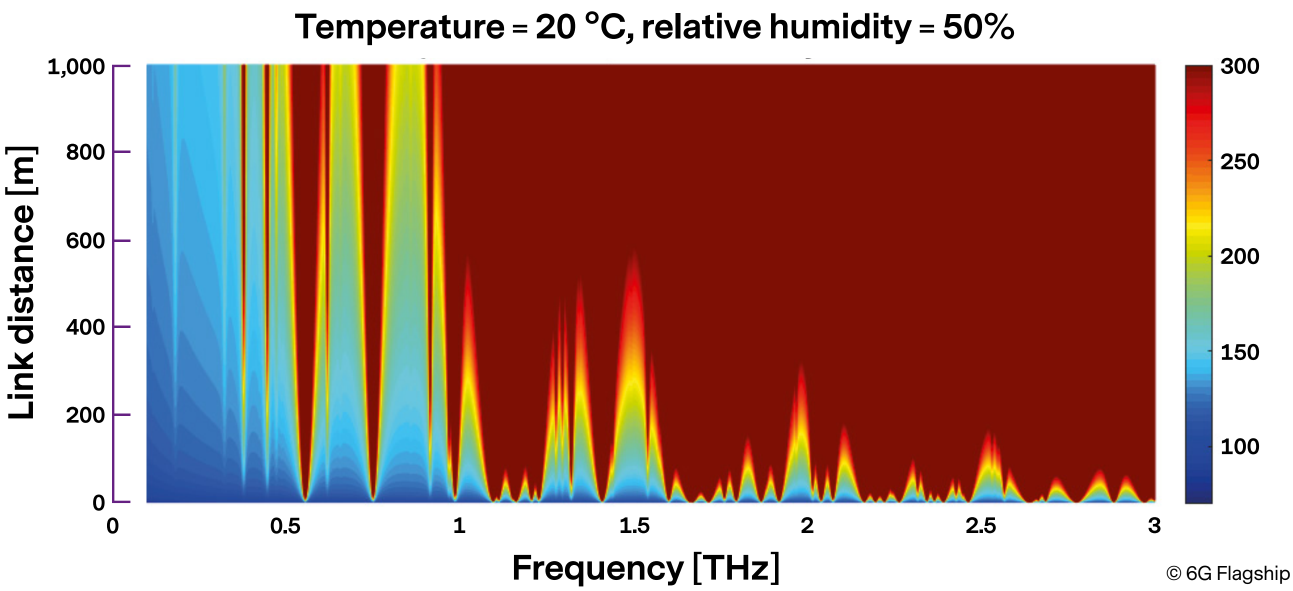


Figure 6.1 Free-space path loss and atmospheric attenuation at frequencies from 0.1 to 3 THz for up to 1000 m link distances.

is the atmospheric absorption due to molecular, and fog and raindrop, interactions. These effects are strongly frequency-dependent, and they affect the field intensity as a function of temperature, humidity, rain rate, and link distance. The atmospheric attenuation has a dB/km rate, i.e. the attenuation in decibels is linearly dependent on the link distance. Short-range and long-range links therefore behave differently in mmW and THz regions. The overall path loss, with the free-space path loss and atmospheric attenuation [TER18] for link distances up to 1,000 m, is illustrated in Figure 6.1. Between frequencies of 0.1 and 3 THz, the figure reveals many transmission windows, i.e. bands with path losses that are tolerable with high-gain antennas. Even between 1 and 3 THz, several spectrum opportunities are provided, with more than 100 GHz contiguous bands for short-range radio links.

6.2 Trends in propagation channel with increasing frequency

Many aspects of the radio channel are clearly frequency dependent, though the dominant propagation paths are often the same, regardless of frequency. At higher frequencies, the physical size of antennas becomes smaller with short wavelengths. Consequently, keeping the same aperture increases the electrical size and makes the antenna more directive. In the following, we list a few trends that are observable in the propagation channel when increasing the radio frequency. The free-space path loss increases, and molecular absorption spectral lines start impacting around 60 GHz (oxygen) and above 300 GHz (water). The diffraction phenomenon becomes weak. The reflection coefficient is almost independent of frequency. Transmission loss through many materials increases substantially, and Fresnel ellipsoids become smaller. Even small obstacles may therefore obstruct the path, but on the other hand, they also act as significant reflectors or scatterers [SEF16]. Moreover, a smaller clearance is needed for paths to avoid obstruction. Surfaces become rougher with respect to the decreasing wavelength, which should decrease the reflection/scattering power ratio. However, the practical significance of scattered power is still not proven by measurements.

6.3 Status of channel modeling

Radio channel measurements are the basis of channel models. Measurements become more challenging with increasing frequency. Dedicated wideband channel sounders with physical arrays of tens (e.g. 52) of dual polarized antenna elements at both Tx and Rx were used at sub-6 GHz frequencies to provide the channel's time, frequency, space, and polarization domain characteristics. It was possible to keep the required phase accuracy and use omnidirectional arrays, while maintaining an adequate link budget. Currently in mmWave bands, this is not generally the case. Most measurements are performed either with highly directive antennas using mechanical rotation, or with virtual antenna arrays [SEF16]. Both these techniques are slow, prevent time-continuous measurements, and limit the achievable amount of measurement samples. At sub-6 GHz, it was possible to drive or walk around with Tx and Rx, and to measure continuously as much as necessary. Currently in mmWave, only a few tens of Tx and Rx location pairs are typically measured, and the environment must be kept static during the process. Going to upper mmWave or THz bands further increases the measurement challenge. Very high antenna gains are needed to compensate for the path loss, and a decent phase accuracy of virtual arrays is mechanically and RF technically non-achievable. The remaining option is to mechanically rotate the pencil beams of Tx and Rx antennas. Taking a full 3D scan with a modest 5° step for two orthogonal linear polarizations, for example, would result in approximately 5,000 measurement steps. If these rotations are performed both in Tx and Rx, the number of combinations to measure is >25,000,000 for each Tx and Rx location pair.

Traditionally, stochastic channel models have specified radio channel effects through different components, such as distance-dependent path loss, some large-scale shadowing, and fast fading (also called small-scale fading). In well-known and standardized models like 3GPP models, the first is an empirical function, and the second is a random variable with a certain distribution. The third component is either modeled as a random process or determined based on random propagation parameters, antenna characteristics, and virtual motion.

Stochastic models require large datasets for the extraction of probability distributions. For the abovementioned measurement reasons, there are numerous radio channel models for sub-6 GHz bands, covering both path loss and fast fading. For the 5G mmWave bands, most measurements have been conducted for path loss only. There is only a few fast fading models for 5G, and at least the standard models are direct extensions of sub-6 GHz models. Only a few radio channel models exist for upper mmWave and THz bands, and those that do are not very general [HC18]. The challenge of stochastic modeling for higher frequency bands leads to an examination of deterministic modeling options.

Ray-tracing techniques can be used for multipath channel models, utilizing the principles of geometric optics to trace the propagation of line-of-sight (LOS), reflected, scattered, and diffracted EM waves. The very short wavelength in the considered frequencies allows accurate modeling with the ray optical approach. Ray-tracing methods have provided good prediction capabilities at 60 GHz, and a similar capability is expected at the 0.3 THz frequency [HBA15]. Deterministic modeling is an attractive alternative to higher frequencies for several reasons: Measurements are difficult; the modeling environment is typically confined, because penetration through building materials can be largely neglected; and path discovery is simpler, because paths are largely specular [SEF16]. On the other hand, higher frequencies also incur challenges for deterministic modeling: The environment description should be more precise, because even small objects and shapes can contribute to the channel (see 2.3 above). A solution for overcoming this challenge is to collect and use LiDAR point cloud data [GCA19] to define the environment to be modeled.

Overall, channel measurements are difficult, and channel models are few, for upper mmWave and THz bands. New measurement-based evidence about the propagation channel is needed. Deterministic modeling can be used with measurements to complement channel characteristics. Traditional channel modeling methods may no longer be fully suitable. For example, is there any need for temporal fading modeling when both the delay and angular resolution of transceivers are extremely high? Or is the traditional distance-dependent path loss model, in which antenna gains are added to omnidirectional path loss, still useful with pencil beam antennas? An alternative in channel characterization to support early simulations is to collect datasets from measurements and make them publicly available with adequate documentation. The playback of such data would enable simulations and other evaluations even before a critical mass of channel data was collected, and more elaborated channel models could be developed.

The use and sharing of spectrum in the 6G era

7

The quest for new spectrum bands for cellular systems comes with each new generation, and 6G will be no exception. The use of the radio spectrum is highly regulated at various levels, all the way from the international agreements at the International Telecommunication Union (ITU) level in the Radio Regulations (RR) revised at the World Radiocommunication Conferences (WRCs) and related recommendations and reports to the regional level, which is via CEPT (European Conference of Postal and Telecommunications Administrations) in Europe, and all the way down to national-level spectrum assignment decisions.

Future communication systems are gradually moving up in frequencies for mainly two reasons: (1) The spectrum below 6 GHz is very occupied; (2) data-intense applications will require more bandwidth than is available at lower frequencies. It is obvious that Tbps communications cannot be performed in the most desired and crowded spectrum below 6 GHz. New applications, like very precise positioning, also require large bandwidths that are only available at lower and upper mmW ranges. As 5G cellular systems are already standardized for several bands at lower mmW range, new opportunities are being studied even slightly above 100 GHz, and IEEE802.11ad/ay standards are also occupying license-exempt bands around 60 GHz, the research interest is increasingly focusing on the upper mmW region and even on THz in considering new opportunities for 6G.

On the other hand, sharing the spectrum wisely and effectively between users and different radio services is also one of the key future challenges due to existing usage in the bands. Range and data-rate requirements typically guide the spectrum use to the lowest available frequency. However, in the competition and collaboration of many radio services, different kinds of user sharing the same spectrum remain a major challenge. New frequencies in the higher bands would enable the transfer of traffic to a less crowded part of the spectrum from below the 6 GHz region. On the other hand, lower frequencies are necessary, even with lower capacity, to maintain connections in the event of dynamic blockages, and especially of mobility.

The rest of this chapter will discuss some of the recent development in 6G-related spectrum regulations and the role of spectrum sharing.

7.1 Opportunities of spectrum use for 6G and related regulations

At the international level, the framework for the use of frequencies is managed by the ITU-R, along with RRs and Recommendations and Reports. Cellular mobile communication systems traditionally operate within the allocation for the mobile service and identification for IMT (International Mobile Telecommunications) systems in the RR, see [RR20]. New bands have continuously been made available for IMT systems at various WRCs. In November 2019, WRC-19 identified 26, 40, and 66 GHz (i.e. 24.25–27.5, 37–43.5, and 66–71 GHz) mmW bands as the global harmonization bands for the IMT system. How to efficiently utilize these bands is as important as finding the new spectrum.

What is interesting is that the current wireless systems can work under a variety of frameworks. For example, in the European regulatory framework, three different categories of solutions enabling various fixed and terrestrial mobile applications in different frequency bands under different regulatory regimes are introduced, including Mobile Fixed Communication Networks (MFCN), fixed point-to-point links, and Short-Range Devices (SRD). The MFCN encompasses traditional cellular IMT systems, but certain use cases envisaged for 6G could operate under fixed or SRD regimes, potentially opening other bands to be used by these systems.

The radio spectrum above 90 GHz has initially been used by passive scientific services (e.g. radio astronomy observation (RAS), earth exploration-satellite service (EESS), meteorology, etc.): See [FCA19] for more details. A total of 160 GHz of spectrum has been allocated or identified in the frequency range between 252 and 450 GHz. The 252–275 GHz band has already been allocated to Fixed Service (FS) and Land Mobile Service (LMS) on a co-primary basis. As the outcome of WRC-19 under agenda item 1.15, new opportunities for land mobile and fixed services applications were approved in the 275–296 GHz, 306–313 GHz, 318–333 GHz, and 356–450 GHz frequency bands. These bands need to be shared with passive services, namely the Earth Exploration Satellite Service (EESS) and Radio Astronomy Service (RAS), see [RR20]. For the use of these bands, sharing studies have revealed no specific conditions to protect EESS applications, whereas specific conditions to protect radio astronomy, such as a minimum distance or avoidance angles, for example, may apply.

Preparations for the next WRC-23 include new studies of IMT systems that for Europe include considering the identification of new frequency bands (mainly 6,425–7,025 MHz), and possible regulatory actions in the 470–694 MHz frequency band. Regarding the higher bands, the sharing feasibility between active and passive services needs to be studied to determine if and under what conditions sharing is possible in the bands above 71 GHz, including but not limited to, 100–102 GHz, 116–122.25 GHz, 148.5–151.5 GHz, 174.8–191.8 GHz, 226–231.5 GHz, and 235–238 GHz. Additionally, studies are invited to determine the specific conditions to the land-mobile and fixed-service applications to ensure the protection of EESS (passive) applications in the 296–306 GHz, 313–318 GHz, and 333–356 GHz frequency bands in Resolution 731 from WRC-19.

7.2 Role of spectrum sharing in 6G

The advent of 6G calls for a fresh look into spectrum sharing. Next, we review the principles of spectrum sharing, followed by spectrum access options for 6G and related technologies.

7.2.1 Principles

In ITU-R terminology, spectrum sharing refers to a situation in which two or more radio systems use the same frequency band [ITU14]. Coexistence in frequency regulation in ITU-R refers to a situation in which two or more radio systems operate in adjacent frequency bands. However, coexistence is also broadly used to describe spectrum sharing between different systems in the unlicensed bands and radio interference in a single device supporting multi-standard radio.

The paradigm of spectrum sharing has been studied to boost spectrum efficiency and spectrum reuse of mobile communication networks, but its real-life applications remain limited, because mobile network operators (MNOs) fear a loss of control and prefer to pay the licensing costs for an exclusive spectrum over a long time-span. Exclusive spectrum use is known to be underutilized in different locations, and a lot of spectrum is therefore wasted. However, as long as an exclusive spectrum is available, neither spectrum sharing nor spectrum efficiency is a major concern. Traditionally, MNOs have deployed their networks by obtaining exclusive nationwide spectrum licenses from the national regulators, often through auctions in spectrum bands allocated for the mobile service and identified for IMT systems by the ITU-R. Spectrum sharing has not been required since the bands have been cleared from existing incumbent usage to be used by the MNO. MNOs typically pay for the license, while the incumbent's non-MNO spectrum users have had different mechanisms for obtaining access rights, which has further complicated the finding of suitable arrangements for spectrum sharing between different wireless systems. In 5G, the variety of frequency bands is higher than before, ranging from sub-6 GHz to the lower millimeter wave region. In 5G, spectrum sharing is gradually taking place mainly in four forms: 1) allowing an MNO to migrate to 5G in a band where it uses prior 3G/4G technologies; 2) protecting selected existing incumbent users (e.g. in the 3.5 GHz and 26 GHz bands in Europe); 3) the assignment of local 5G spectrum licenses involving inter-operator spectrum sharing; and 4) the development of unlicensed access variants of the 5G systems. The levels of spectrum sharing vary in these different deployment models.

The 6G era faces even more dynamic operational environments. Finding new spectrum for cellular systems has become a bigger challenge due to rivalry with the bands' existing spectrum users, such as satellite and broadcasting, and spectrum sharing is becoming a necessity. The challenge is to define spectrum-sharing rules, conditions, and mechanisms that ensure that incumbents remain free from harmful interference, and entrants have favorable deployment opportunities. In practice, this has been very challenging due to overstated protection requirements from the existing users, which has led to the conclusion that spectrum sharing between the different systems is not possible in most cases.

7.2.2 Classification and options for 6G

There are several ways to define a classification for spectrum sharing. Fundamentally, two forms of spectrum sharing are defined here:

- **Horizontal spectrum sharing** (also called co-primary sharing in ITU terminology) is sharing between systems with the same level of rights to access the spectrum.
- **Vertical spectrum sharing** is sharing between systems with different levels of rights to access the spectrum.

Vertical and horizontal spectrum sharing are not mutually exclusive, and they can both exist in real situations. For example, spectrum sharing in the "unlicensed" bands includes horizontal spectrum sharing, because technologies (e.g. Wi-Fi, Bluetooth, and IEEE 802.15.4e) share the band with similar rights. At the same time, vertical spectrum sharing can protect existing spectrum users with a higher level of access rights in some countries. Users or systems with different levels of spectrum access rights are sometimes called primary users (PUs) and secondary users (SUs), where the PUs have the prime right of operation, and their transmissions must not be compromised, while the SUs can opportunistically use the spectrum when it is not occupied by the PUs. SUs must take appropriate measures to avoid creating harmful interference with the PUs, as defined for the specific spectrum band. Spectrum sharing is especially important in sub-6 GHz bands, where spectral bands do not increase, while demand for traffic continues to grow.

Table 7.1 provides an overview of relevant spectrum access models for mobile communications systems and summarizes the level of spectrum sharing in the models that are also relevant for 6G systems. The complexity of operations is already growing in 5G and continues to grow in 6G as the variety of spectrum access options increases, and there are national variations in the approaches leading to fragmentation––see [MYA20]. At the same time, the realization of spectrum sharing becomes easier in higher frequencies, where the interference distances also remain limited.

Spectrum access model	Description	Deployment	Level of spectrum sharing	Example bands and technologies
Exclusive licensed access	A regulator assigns a license to an MNO with exclusivity to operate in the given band and area according to rules defined in the licensing agreement.	A single MNO in a given geographical area can operate free of harmful interference.	Typically involves no spectrum sharing.	GSM, UMTS, LTE, 5G in auctioned bands.
Intra-operator spectrum access	An MNO shares its spectrum resources across the different network technologies that it operates.	An MNO can deploy different technologies in the same licensed band. For example, 5G deployed in collaboration with 2G, 3G, or 4G	Spectrum sharing is an MNO internal matter in its own band. For example, MNOs' 5G network dynamically shares the spectrum with its 4G network.	Technologies called "dynamic spectrum sharing" in 5G by vendors in existing IMT bands.
Unlicensed access	License-free operation according to national regulation, which may impose geographical restrictions (e.g. on power levels, duty cycle, and the need for LBT)	Anyone can deploy equipment that follows the rules.	Horizontal sharing between devices. Vertical spectrum sharing to protect higher priority users, case-by-case.	WiFi, ZigBee, Bluetooth. LTE-U
Spectrum trading/ leasing	Deployment of the network in a band with access rights obtained from an MNO through a trade/lease.	Requires a contract with an MNO.	Sharing can occur between an entrant and the MNO according to rules defined in the agreement.	4G and 5G in auctioned bands.
Local licensing	Band is assigned to local or regional providers based on predefined criteria.	Local deployments in geographically defined areas.	Horizontal sharing between local license holders according to defined rules. Vertical sharing to protect possible incumbents.	4G/5G in 3.5 GHz band in some countries.

Spectrum access model	Description	Deployment	Level of spectrum sharing	Example bands and technologies
Licensed Shared Access	Additional licensed users are introduced to a band currently in use by incumbents, allowing all users to provide a certain quality of service.	Allows a service provider to deploy a network with quality guarantees while having to protect incumbents.	Vertical sharing to protect incumbents and horizontal sharing with other potential additional licensed users.	2.3 GHz discussions for sharing between 4G/5G and program making & special events (PMSE). LSA database and controller needed.
License-assisted access	Use of unlicensed band in conjunction with a licensed band.	An MNO boosts its network capacity by expanding operations to an unlicensed band while also using a licensed band.	Horizonal sharing in the unlicensed band according to the band's rules.	LTE-LAA, 5G-NR-U, requires carrier aggregation of licensed and unlicensed bands.
Spectrum pooling	Operators can collectively use a band under agreed rules.	Adds flexibility to balance supply with varying demand.	Horizontal sharing between operators participating in pooling. Vertical sharing with protect potential incumbents.	5G in 26 GHz band in some countries.

Table 7.1. Relevant spectrum access models for mobile communication networks.

Despite the higher capacities available at the recently introduced and new mmWave frequencies and beyond, the sub-6 GHz frequency region will always be popular because of its favorable propagation properties. As recently proven in [DARPA], multiple heterogeneous wireless systems, each with their own radio access technology (RAT), can share the same spectrum without colliding and still fulfill strict quality of service (QoS) requirements by combining spectrum-sensing techniques, agile physical layers (supporting numerology like 5G-NR, power control), flexible MF-TDMA (multi-frequency time decision multiple access) MAC strategies, distributed resource allocation schemes, assisted with AI techniques and collaboration protocol for sharing information between co-located networks [GDM19, FJL18, MCF19]. In the spectrum-sharing model, multiple networks by different network operators share the same spectral resources. In shared spectrum environments, distributed algorithms in which the receiver decides on spectrum allocation may be more appropriate, as collisions only happen at the receiver. Initial experiments [DARPA] show great potential, evidencing higher spectral efficiencies and high spectral reuse in shared bands compared to exclusive shared bands.

7.2.3 Related technologies

Operations in a variety of spectrum bands are among the most important research directions in the 6G spectrum management area. The management involves different levels of spectrum sharing, using a mix of centimeter, millimeter, and terahertz waves. This introduces more challenges and calls for more efforts to overcome concerns related to the combination of different bands with heterogeneous features. To protect the existing incumbent spectrum users and coordinate potential interference between local users, database-based approaches will remain an important tool. The role of spectrum monitoring through measurements has been limited to date. However, the envisaged 6G capabilities for obtaining accurate situational awareness [LL19] may change the networks into accurate measuring tools, including awareness of the surrounding spectrum use.

For unlicensed access, Listen Before Talk (LBT) in its conventional form does not work for mmW and THz bands due to the use of directional communication, because the transmitted beams can no longer be detected due to the directivity of carrier sense, which can result in inaccurate spectrum occupancy decisions. Some nodes can become invisible to other nodes that are not positioned in the direction of their beams. LBT mechanisms therefore need to evolve to fit the 6G requirements, and it is worth saying that cooperative and distributed LBT seems a good technically feasible solution [LGG20].

Operations in multiple spectrum bands ranging from licensed spectrum to unlicensed and shared frequencies call for **new advanced carrier aggregation methods** for 6G, as shown in Figure 7.1 [JFR19]. For each transmission, a selection of multiple bands in accordance with the intended service/application requirements, terminal capabilities/categories, and network conditions is performed to optimize the bandwidth. The ACA paradigm always enables connectivity via the remaining bands in case an interference or collision occurs in some bands. It can ensure robust and transparent mobility with enhanced overall throughput, spectral efficiency, and cell-edge performance. The ACA scheme uses a licensed spectrum as the primary carrier for signaling, and carrier aggregation is used to include additional secondary component carriers in various spectrum bands to deliver higher data rates to customers [CI19]. It offers a flexible spectrum utilization, and therefore a scalable bandwidth, which is very suitable for rich digital and multimedia content that is highly sensitive to fluctuating environmental conditions. Adaptive compression and source coding can be employed before transmission to display an adapted quality on the receiver side [CI19].

Evolved multi-connectivity integrates multiple RATs with the aggregation of traffic flows among various bands, as illustrated in Figure 7.2, where multiple links flow from many sources to one destination in both uplink and downlink. It can increase the available bandwidth and provide seamless mobility. It is also a robust approach for tackling the load-balancing issue among the nodes in the network to improve fault tolerance and service resilience, especially in virtualized networks. The aggregation of these bands can be technically achieved at various layers: radio link; IPL; TCP; etc.; or at various architecture levels: Radio Access Network (RAN; Core; or service. Multi-connectivity can be exploited for both standalone and non-standalone deployments.

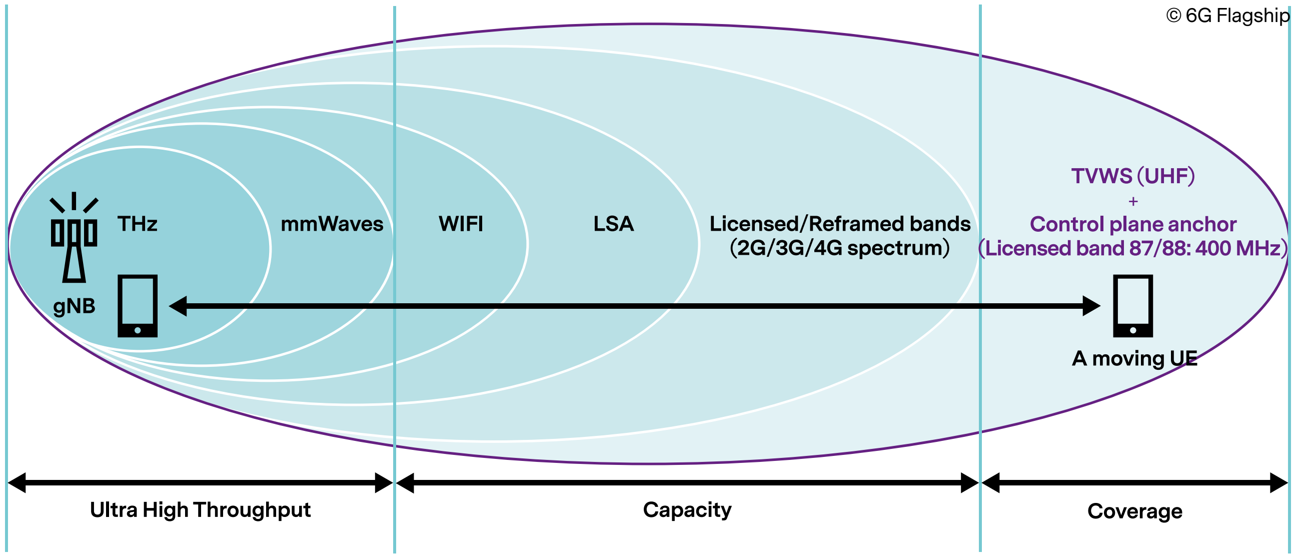


Figure 7.1: Advanced Carrier Aggregation.

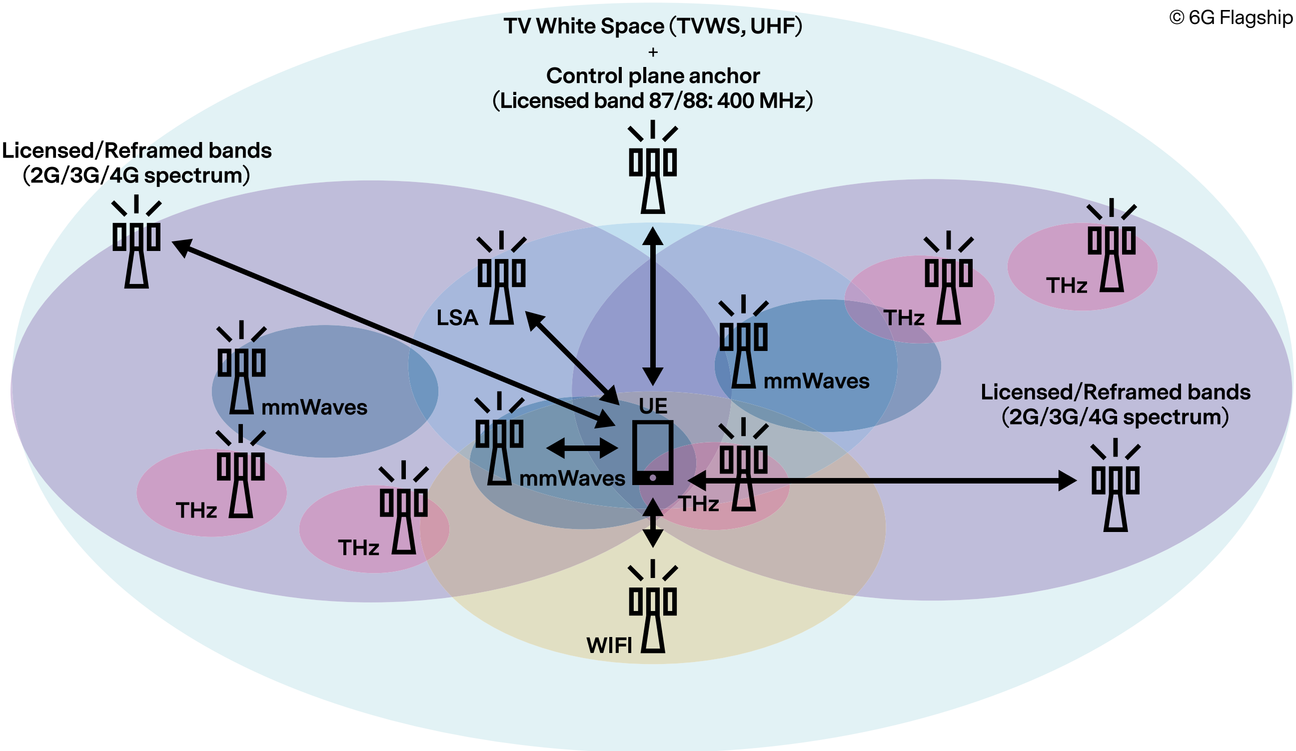
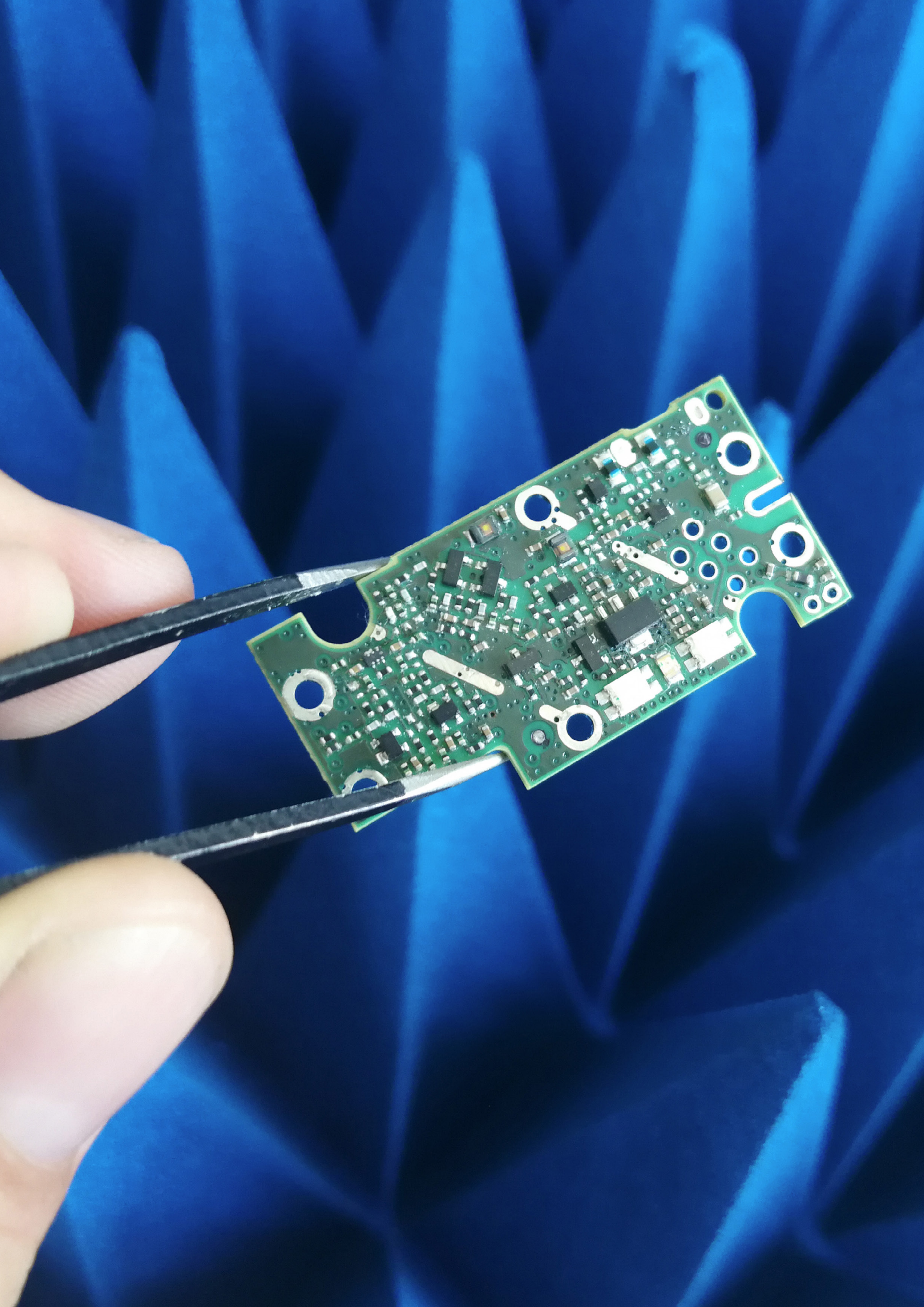


Figure 7.2: Evolved Multi-Connectivity.



Prototyping and testing future systems 8

New sub-THz frequency allocations for 6G systems will challenge the prototyping and testing of new 6G devices in multiple ways. First, the frequencies are higher, and wavelengths are therefore much shorter than even in 5G Frequency Range 2 (FR2, 24.2–52.6 GHz) at the lower mmW spectrum. Not only does this move us further into difficult territory with semiconductor physics (gain, bandgap, carrier mobility, cost, fabrication, noise power density, etc.); we also face the increased challenge of reduced physical dimensions. The physical dimensions of new components and related new devices will be smaller than at lower frequencies. As absolute physical dimensions reduce, tolerances in the physical dimensions of electrical components, mechanical parts, as well as assembly accuracies will introduce significant variation to the radio performance. Challenges also include the much wider baseband bandwidths with associated high-speed signal processing and power requirements, as well as the much higher levels of integration of radio systems to avoid performance degradation due to signal power loss at the most critical nodes in the system.

To overcome the related complex prototyping and testing of radio performance, the radio solution should be simulated in detail with electromagnetic (EM), circuit-level, and system-level simulations. The cost of printed circuit boards and prototypes with such small dimensions and exotic materials means that simulation will be much more necessary to avoid design turns and rework, as well as to facilitate troubleshooting. In addition, the increased integration level of future 6G radio circuitry emphasizes the need for detailed simulations, because direct measurement for debugging the radio by testing of the individual components and antennas will not be possible.

In addition to EM and circuit simulation, system-level simulation will be needed to evaluate performance requirements and system-tradeoffs for the transceiver. Sub-terahertz or terahertz systems operating over wide or extreme bandwidths will require careful consideration to optimize performance. Key design considerations include optimizing signal-to-noise ratio (SNR), minimizing LO phase noise, addressing linear and nonlinear impairments, optimizing energy efficiency, and evaluating candidate waveforms. All these will become much more difficult targets to achieve as we move in frequency to the upper mmW region and above. These design considerations should also be considered for R&D testbeds to address the bandwidth and performance demands for 6G research.

The testing of the 6G radios will continue and expand on the same path as FR2 5G radios, which rely on over-the-air (OTA) testing instead of classical conductive test points at lower frequencies. And the challenge is that OTA testing is mainly performed at the system-level, where baseband (BB) test signals are provided to the device under test (DUT), and the performance of the RF is often done by analyzing demodulated BB signals at the other end that have passed through the OTA radio link. Such a measurement approach measures the entire radio performance of the radio solution without the possibility of testing individual components.

It is envisaged that 6G radios will support data rates of up to 1 Tbps, which requires an extremely wide information signal bandwidth (BW) at the BB frequency. Here is an example of how extreme this could get:

Recent demonstrations of 5G systems have shown 4.2 Gbps data rates using eight aggregated 100 MHz carriers at 28 GHz. Even if the industry can double this spectral efficiency (5.25 bps/Hz to 10.5 bps/Hz—an almost unheard-of spectral efficiency in practical applications), it would translate to a 95 GHz information bandwidth for 1 Tbps.

Thus, the generation and analysis of the wide BW BB will require new measurement equipment to support these requirements. Such measurement equipment and DUTs to support data rates of up to 1 Tbps will require new high-speed and high-performance analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), as well as a new high-speed digital logic such as field-programmable gate arrays (FPGAs). The use of such new components will increase the initial cost of 6G DUTs and measurement equipment.

Prototyping and test specifics

Since 6G requirements are not yet strictly defined, R&D testbeds should be flexible to address different candidate frequency bands, modulation bandwidths, and candidate waveforms [JUE20]. They may also need to be scalable to multiple simultaneous channels to investigate multiple antenna techniques to increase data throughput. The fundamental architecture of an RF transceiver testbed includes baseband generation, modulation, and translation to RF carrier frequency, DUT interconnection (Tx and Rx), the RF receiver, demodulation/downconversion, baseband processing and analysis, and software to enable each of these steps, as well as calibration and data management.

Addressing components and devices

Some conductive testing will still be feasible with 6G sub-THz radios. This will be performed mainly with frequency extenders connected to RFIC probes via a waveguide connection, but the RF probe testing is limited to conductive RFIC-level testing. The waveguide connections add the complication of restricting the physical locations and orientation of the measurement equipment and DUTs. Thus, there will always be a fundamental need to measure components, both passive and active, with vector network analysis (VNA). At these frequencies, this will be done using wafer probe techniques with frequency extension capabilities on VNAs. New capabilities in VNAs also include some broadband, large-signal (non-linear), and noise figure (NF) characterization, which will help the assessment especially of active devices where these issues are critical in communication systems.

Addressing wider bandwidths

The test signal generation will happen at baseband with high-performance arbitrary waveform generators (AWGs), high-performance real-time generators (e.g. using FPGAs), and software for control and manipulation of frame-structures, waveforms, and modulation. AWG's can achieve up to 70GHz of analog bandwidth with sampling rates of 256GSa/s across multiple channels. Many of these systems can generate a modulated intermediate frequency which can then be directly translated to the carrier in question. Low residual Error Vector Magnitude (EVM) performance can be achieved, especially at lower intermediate frequencies (IF) due to oversampling processing gain from the AWG's high sampling rate. Consideration should be given to selecting an IF frequency that is sufficiently high to allow for filtering the undesired image product after upconversion to the sub-terahertz frequency band, but sufficiently low to achieve optimal EVM performance with the oversampling processing gain from the AWG's high sampling rate.

The first step in performing the test signal analysis is some form of frequency conversion (downconversion) from sub-terahertz frequencies to an IF. High-performance real-time oscilloscopes or digitizers will be required to address the wide bandwidth requirements for 6G. For example, high-performance real-time oscilloscopes can currently achieve up to 110 GHz of bandwidth, with sample rates of up to 256 GSa/s across multiple channels. Oscilloscopes and digitizers can be combined with downconverters to analyze sub-terahertz signals with these wide bandwidths. Consideration should be given to properly scaling the IF amplitude to the digitizer to optimize the dynamic range and maximize SNR, which is necessary for optimal EVM performance. The digitized IF waveform would be post-processed using Vector Signal Analyzer (VSA) or measurement software, which can decimate and resample the signal (if needed) for the desired measurement frequency span to measure the spectrum, constellation, and EVM.

The baseband tools mentioned above (AWGs, oscilloscopes, and digitizers) are inherently multi-channel instruments, which can enable scaling the number of channels for multiple-input multiple-output (MIMO) research to increase data throughput using multiple antenna techniques. These need to be combined with multi-channel RF systems which can add to the cost, complexity, and footprint of the testbeds, but offer the benefits of simultaneous channel management required by MIMO systems.

Addressing higher frequencies

Test signal generation for 6G frequencies will require external upconverters. For example, AWGs can be combined with D band (110–170 GHz) and G band (140–220 GHz) upconverters to generate sub-terahertz signals with very wide bandwidths. Flexibility for different frequency bands is accommodated by using different frequency converters. Testing can be performed conducted, by connecting waveguide, or OTA using antennas (e.g. horn antennas). Upconversion from an intermediate frequency (IF) to sub-terahertz frequencies involves frequency translation with a local oscillator (LO) signal source(s) and frequency converter(s). Any frequency multipliers present are usually only used in the LO path rather than the signal path to avoid impacting the signal modulation characteristics. A frequency multiplier will increase the phase noise by at least 20Log(N), where N is the multiplication factor. Furthermore, the multiplier can introduce additive phase noise that will further degrade the multiplied LO phase noise, depending on the quality of the multiplier used. Low residual EVM test system performance at sub-terahertz frequencies requires high-quality, low-phase-noise LO signal sources.

The signal analysis at the D and G bands requires downconverters to be used to convert sub-terahertz signals to an IF. The IF waveform would be digitized and post-processed using VSA or measurement software, which would decimate and resample the signal (if needed) for the desired measurement frequency span to measure the spectrum, constellation, and EVM. In addition to phase noise, in-band spurious outputs from the upconversion and downconversion can impact EVM. Linear errors from filters and other components in the system that have amplitude and phase response vs. frequency can also impact EVM but may be mitigated using an adaptive equalizer in the VSA software post-processing of the digitized IF. A non-linear error from non-linear mixers and amplifiers compressing, phase noise, and spurious outputs will not be addressed by the adaptive equalizer and can impact EVM.

Addressing active antennas

Active antenna arrays with analog beam steering became a typical element of 5G systems in the 24–52 GHz frequency range, and this trend will continue with the higher frequencies proposed for 6G. Three major impacts on the test process are related to active antennas. The first is the increased need to test signal directivity in addition to traditional radio performance parameters. Not only is it important for the signal to be correct, it needs to be pointed in the correct direction. The second large impact on the test process was the removal of connectors at the radio frequencies, requiring that a much higher proportion of testing needed to be performed over the air than with conducted tests performed at lower frequencies. This created a demand for significant numbers of OTA chambers. Previously, chambers were a rarity in the mobile development process. With the introduction of FR2 and active antenna arrays, most test stations now require a chamber for over-the-air tests. The third impact was the additional need to calibrate the array for beam-steering accuracy. For FR2, beam widths were relatively wide, allowing for some inaccuracy in the array calibration process. Indeed, many designs considered that array calibration might not be required. As active antennas for 6G frequencies emerge, it is quite evident that the beam widths will become narrower, requiring more accurate calibration of the phased arrays.

Addressing higher levels of integration

Higher levels of integration and smaller mechanical tolerances will accentuate the challenges already experienced in the measurement of 5G FR2 systems, and it will become very challenging to measure subsystem and component-level performance. First, this accentuates the need for thorough modeling and simulation: EM simulations are needed not only for the RF IC level but at the antenna level. Furthermore, these need to be co-simulated (as a circuit), because antennas and RF ICs will merge into the same circuitry. The 6G antennas at sub-THz frequencies will utilize antenna arrays and arrays of multiple antenna types such as patches, dipoles, reflectors, or perhaps even lenses, forming an antenna system to enhance the radiation performance of the 6G radio. A system-level simulation that considers subsystem and component-level interactions will thus facilitate a faster and less-expensive prototyping process. This will require the advanced modeling of the semiconductors, passive elements, packaging, interconnects, and antennas.

In 4G and previous generations, almost all base station and mobile station device testing done in research and development (R&D), manufacturing, and conformance tests (CT) used conducted or cabled measurements. Testing of cellular communications devices has already changed with the introduction of FR2 5G systems due to the use of integrated antenna arrays and beam steering at both ends of the radio link. The use of and direct integration of antenna arrays with multiple antenna feeds means that conductive testing is cumbersome or even impossible. For example, all 5G NR FR2 conformance tests for radios must be performed over the air.

While it would be advantageous that some conducted testing could be performed with traditional RF testing procedures (e.g. with flexible RF cables and connectors), these testing opportunities will be more limited in the forthcoming 6G systems. The state of the art in conducted testing with cables is limited to 110 GHz or perhaps a maximum of 145 GHz with the currently available RF connectors. 1.0 mm coaxial connectors support RF measurements up to 110 GHz, while the new 0.8 mm connector will reach 145 GHz. However, the 1.0 mm connector type is the smallest connector type with performance that is traceable to the International System of Units (SI) [HWR16]. The advantages of conducted testing over OTA testing are improved repeatability and reproducibility, cost, and test-system physical footprint/volume. It will be important to study how sub-THz high-frequency measurements, both continuous wave (CW) and modulated signal measurements, can be performed with good accuracy and repeatability.

OTA testing, which is already becoming more widespread when testing the lower mmW band, i.e. 5G FR2, will be the most practical approach for testing sub-THz radios. This will be required not only for antenna measurements as described below, but for virtually all radio performance and functionality measurements. There will be a wide mix of measurement types, each with its own set of challenges, and in the case of frequencies above 100 GHz, some relief from at least some of the issues related to NR FR2 testing. The radio performance will need to be measured as with any radio, but with several added test requirements. The fundamental transmitter requirements of output power, spurious outputs, adjacent channel power, modulation accuracy, and occupied bandwidth are all still required. In addition to these, dynamic measurements associated with time division duplexing (TDD) systems, including on/off ratio, switching time, and time masks are needed. With electrically steerable antennas, which are directly controlled by the medium access control (MAC) protocol layer, additional tests related to spherical coverage, beam-switching time, effective isotropic radiated power, and even beam correspondence to maintain the link will all be necessary. This last group is unique to OTA measurements, and requirements in 6G will be more stringent, given the smaller wavelengths.

Measurements that must be made in a low power spectral density environment (e.g. spurious outputs, on/off ratio, and even some beam-searching) suffer from signal-to-noise ratio problems in 5G systems. The distance required between Tx and Rx antennas to ensure that the Rx antenna is in the radiated far field entails significant path loss, and hence dynamic range problems in the measurement. This will be more challenging, given the expected lower output power from sub-THz radios. One might consider mitigating factors related to the possibility of a shorter physical distance between Tx and Rx antennas in an OTA chamber, i.e. a "closer" far field. However, the far field may not necessarily be less than that for 5G FR2. The $2D^2/\lambda$ rule of thumb for far-field distances has wavelength in the denominator which, depending on the size of the antenna aperture (D), could yield a far field that is closer than originally expected.

Another critical issue in OTA testing will be the design, calibration, and use of measurement probe antennas and related signal routing within anechoic chambers. All these topics are relevant to ensure accurate repeatable performance measurements of not only the antennas but the fully integrated system.

System-level considerations

System design software and vector signal analysis software can be used with AWGs, oscilloscopes, and digitizers to provide design-to-test continuity and software-defined flexibility in creating and analyzing different candidate waveforms.

The integration of tools, data, and processes across the system-level design and test steps can greatly improve the overall development process. Typically, the complete system performance needs to be simulated and analyzed. As prototype subsystems become available, they will be tested at the subsystem level, and it will be important to have a toolset that allows the integration of actual test data with the system-level model. In addition, for result consistency, it will be beneficial to have analysis tools that can operate both on simulated data in the system simulation and actual measured data from the test equipment.

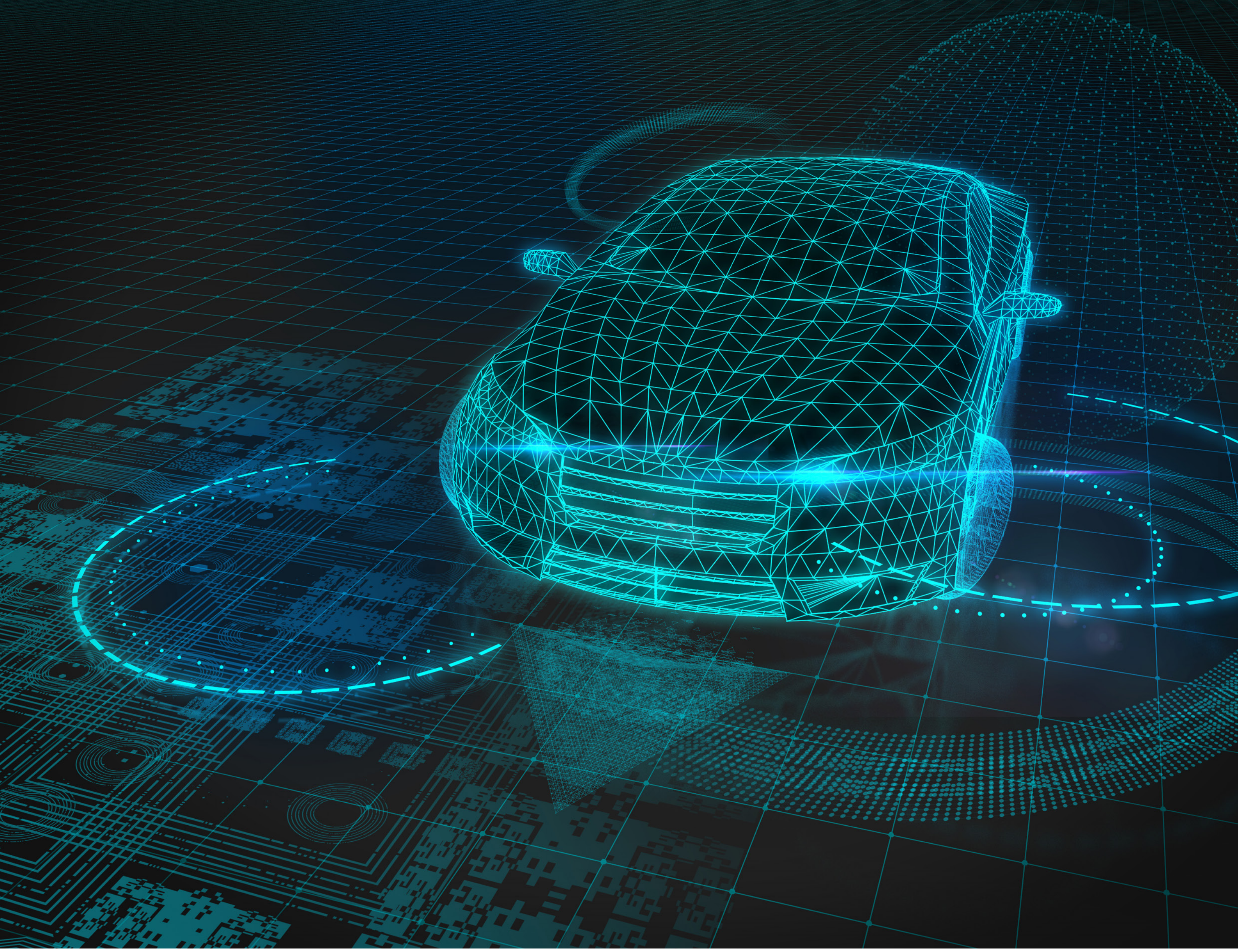
Application-level considerations

The use of radio systems with very short wavelengths lends itself not only to large data rates but to the intriguing possibility of using the radio as a sensor—either to analyze materials or to provide the possibility of radar-like sensing or imaging. These use models are under serious consideration for 6G, and will therefore place an additional demand on testing for systems that are not merely designed to maintain a link with a partner system but to be programmed to measure the reflected responses of their own signals. The approach of using orthogonal frequency division multiplexing (OFDM) in automotive radar systems rather than the simpler FMCW (frequency-modulated constant envelope wave) is already being developed—complex waveforms will be used for ranging and perhaps for the rough imaging of systems. This also allows such radar systems to be less susceptible to jamming and can serve multiple purposes in inter-vehicular communication.

Let us imagine a 6G sub-THz radio system that is designed to maintain a link with an active antenna with another 6G UE or 6G base station, and that can be used for imaging or range finding. In this case, the performance measurements are expanded. The receiver must be reconfigurable (or duplicated) to receive and analyze reflected signals. Thus, now radar-related figures of merit become more critical in 6G systems that would otherwise be subject only to radio link-related figures of merit. Phase noise, already critical for EVM performance in OFDM and related waveforms, is a limiting factor in imaging for both Tx and Rx performance. This also changes how resistance to interference is measured.

Inter-system considerations (working with radios in traditional bands)

While we are only now starting to explore how to bring these bands into mainstream commercial use, operating in sub-terahertz and terahertz frequency bands could offer some immunity to interference due to directional antennas, narrow beamwidths, and propagation attenuation. However, if 6G systems are integrated with 5G Frequency Range 1 (FR1, <6 GHz) and FR2 systems, testing for coexistence will be important. For example, testing FR1 coexistence with legacy wireless signals, or testing FR2 coexistence with satellite signals, may require a flexible testbed to generate and analyze a variety of different test signal scenarios.

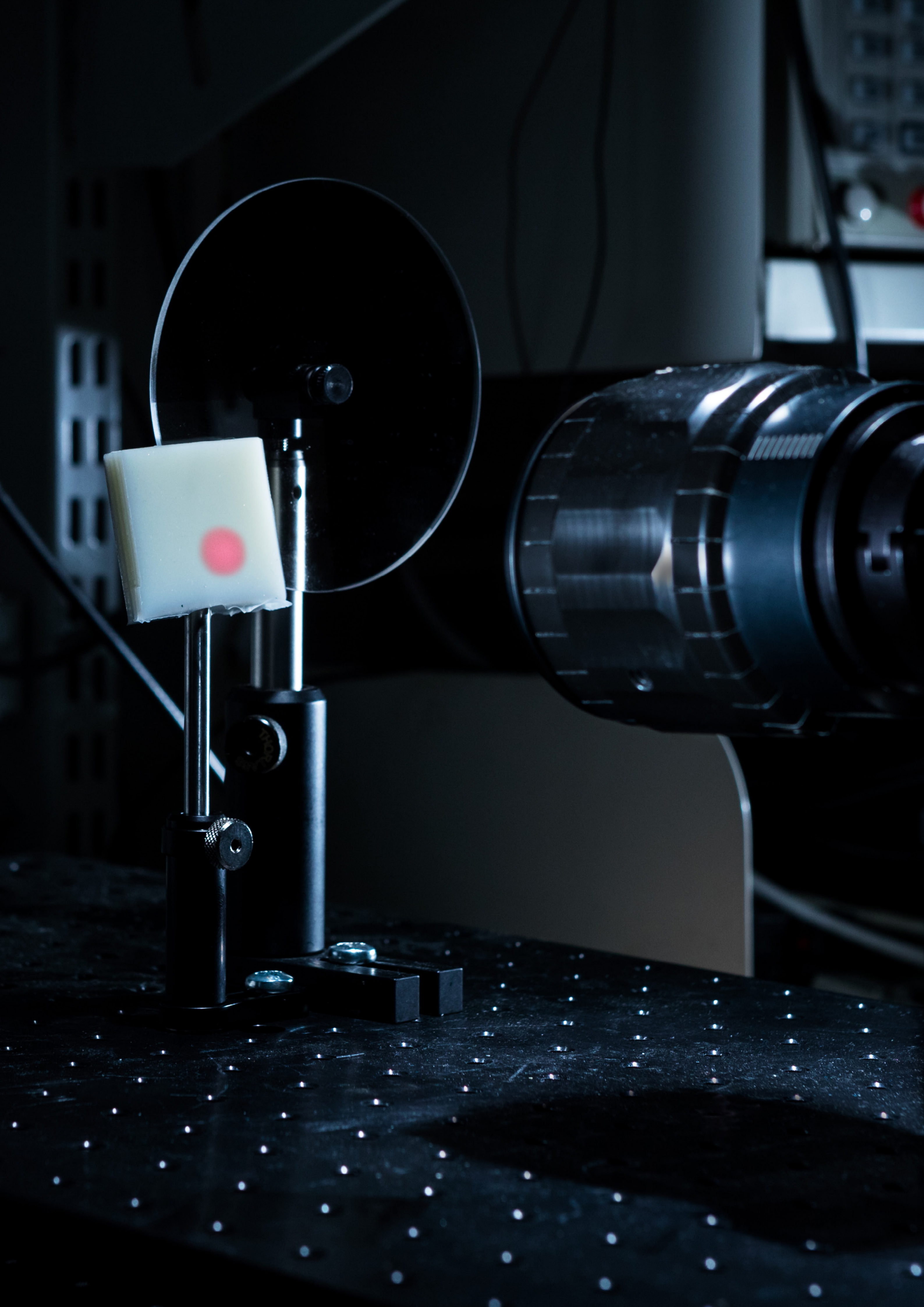


Once the basic capabilities of the new frequency bands, bandwidths and waveforms under consideration for 6G are proven, a major topic to consider will be how this will be integrated into the cellular standards with many years of legacy development and billions of dollars in existing investment. In the early days of 5G, many novel approaches were considered. Many of these approaches would have required significant changes and/or scrapping of previous investments. One way to look at the evolution of 5G is to say that there was a moderate level of change to the sub-6 GHz radio specifications and the inclusion of FR2 frequencies to provide high data-rate channels, when needed and when available. Terms describing the use of FR2, such as “non-standalone” and “enhanced data channel” reinforce this view. As the 5G standard becomes fully deployed, it is possible that this could change, but it is also quite likely that the current approach could remain the long-term reality.

6G will also explore and investigate many novel approaches, in carrier frequency, bandwidth, and waveforms, along with other totally new ideas. However, it is likely that these new ideas will need to work with or augment the standards that preceded them.

From a testing perspective, this will have little impact during the early stages of research and development. However, as fully functional systems are implemented and tested, the test equipment and environment will need to support a very wide range of carrier frequencies and bandwidths. Equipment such as base station and UE emulators will need to support the broad range of frequency bands configurably and cost-effectively. Over-the-air chambers will need to flexibly support multiple antenna locations and frequency ranges. In an eventual 6G UE, it is likely that a call or data session will first be established and maintained using a sub-6 GHz channel, and then the sub-terahertz channel will be added to provide the breakthrough data rates that 6G will promise and deliver.

Just as with the use of FR2 for 5G, the move to bands that use more than 100 GHz will be a novel approach in mainstream commercial communications. The newness of these bands for this application will require extensive work, not only to design working systems but to build the prototypes, and ultimately to measure their performance.



Optical wireless communications

9

The increase in the use of wireless services over the last two decades has led to RF spectrum exhaustion, giving rise to the development of complementary solutions. A possible way to satisfy the requirements of more capacity and less latency is to further reduce network cell sizes (an attocell network) compared to the current "femtocells." The future coverage of a single cell will be a few dozen square meters, e.g. one cell for each room in a house. In this context, optical wireless communications (OWC) are envisaged to support traditional RF technology. Traditionally, RF observes restrictions limiting use, including interference with other communication and navigation systems, disruptions due to bandwidth limitation, congestion leading to a low speed or inefficiency, strict spectrum regulation policies, and security issues from RF waves penetrating walls. To complement the increasingly scarce RF spectrum, OWC has gained considerable interest due to its potential for high-speed, high-fidelity, and low deployment cost features. Moreover, free-space optical (FSO) communication and visible light communication (VLC) technologies have several advantages, including license-free operation, a large amount of available spectrum, robustness against interference, and more potential for secure communications.

9.1 Free-space optical communications

FSO systems rely on optical radiations, with wavelengths in the infra-red range, to convey information in free space. These systems rely on laser diode sources that convert the electrical signal to an optical signal, and photodiode receivers that convert the optical power into an electrical current. As such, light beams propagating through the atmosphere can carry the information from the transmitter to the receiver while not being too demanding in terms of infrastructure. However, FSO links are greatly affected by weather conditions and atmospheric turbulence. Fog attenuates the optical signal, leading to the FSO link's unavailability. Due to variations in the atmospheric refractive index, turbulence-induced scintillations severely degrade FSO link performance. However, FSO links can be properly complemented by RF links in "hybrid" RF/FSO systems to alleviate the previous disadvantages.

Some interesting research directions that need to be pursued over the coming decade for the development and more massive deployment of FSO by the 2030s include:

- The development of low-cost pointing, acquisition, and tracking schemes.
- The design of novel adaptive optics and signal-processing schemes to mitigate the effect of wave front distortions due to atmospheric turbulence.
- An increase in the capacity of FSO links, using spatial mode multiplexing such as orbital angular momentum (OAM) modes.
- The further development of Quantum Key Distribution (QKD) when implemented over high-speed long-haul FSO backhaul/feeder links for nearly perfect security.

The use of FSO as **high-speed wireless backhau**l [DDA16] is a promising backhaul solution. Traditional technologies for backhaul terrestrial networks include either RF backhauls or optical fibers (OF). While RF is a cost-effective solution compared to OF, it supports lower data-rate requirements. However, unlike OF links, which are always reliable, FSO links are sensitive to weather conditions like fog, snow, and rain. Reliability should therefore be considered when designing FSO-based backhaul networks. To cope with the varying reliability and combine the advantages of RF (reliability) and FSO (capacity), hybrid RF/FSO technology is a suitable complementary option to upgrade the existing backhaul networks and serve emerging/future integrated backhaul access (IBA) deployments.

Unmanned aerial vehicles (UAVs) [ASY18] are a strong candidate for deploying on-the-fly networks, in which

they can provide powerful scalable moving networks in the sky. This flying network can provide connectivity for aerial and terrestrial users. The flexibility of the UAVs' location allows the deployment of the network at different altitudes, while providing different degrees of coverage and data rate. The UAV network can adopt high-speed FSO for inter-flying platform connections and vertical feeder links, with optical gateway stations on the ground.

Wireless data center communications [CAS19] are attracting growing interest, because wired data center networks may suffer from cabling complexity and oversubscription. In this context, wireless inter-rack connections can be established using FSO for both line-of-sight (LoS) scenarios and non-LoS links, relying on a mirror fixed to the ceiling.

9.2 Visible light communications

Recently, research in the OWC field has focused on communication operating in the visible band (390–750 nm), commonly known as visible light communications (VLC). VLC uses an LED light as the antenna in the RF to transmit data in the optical frequencies of the visible band. The line-of-sight communication feature offers a high degree of spatial confinement, and this can allow the creation of a small cellular network. VLC technology is based on the use of an LED light as a source, and a photodiode as a receiver. The light is modulated by varying the intensity, thus mapping 0 or 1 directly into the optical wave. The modulation of the light must be sufficiently fast to avoid a flickering effect. Integrating VLC technology with the 5G network has been tested [NPC19]. However, optical wireless communications are not included as enabling technology in the 5G standard, because VLC was not commercially ready when the research into 5G started. VLC technology has now reached a good level of maturity. VLC is considered a potential medium for wireless communications, and it is gaining popularity in multiple industries. VLC has strengths in energy efficiency and an ultra-wide bandwidth. At the same time, as a relatively new technology, it is still steadily growing in transmission range and overcoming obstacles in transmission paths. In addition, accurate localization is another feature of VLC that is now well investigated, including performance in different environments, and NLOS component detection and mitigation. Finally, VLC can also be used for simultaneous light wave information and power transfer (SLIPT) to provide energy-harvesting capabilities to user units.

In future 6G networks, the two technologies (RF+VLC) could coexist, and 6G could benefit from VLC features like potentially high bandwidth, low latency, energy efficiency, and different security mechanisms. A hybrid RF-VLC solution could be beneficial for both technologies, because RF can complete the VLC limitations. The use of optical wireless attocell networks could increase the data rate and reduce the latency in 6G systems. VLC has the additional feature of being a "green solution": the same energy can be used for illumination and connectivity, supporting the wider spread of the 6G network. The latest solutions of flexible optical materials also make VLC technology suitable for wearable applications. It will be necessary to develop appropriate handover methods to manage network cell, physical layer security techniques, and a new protocol for every communication layer and multi-user set-ups [OSA19]. Moreover, the telecommunication requirements (e.g. high-speed modulation and low noise) will be important in optimization for new LED manufacturing in the opto-electronic research field.

The visible light spectrum is globally unlicensed and can be used to communicate freely with low power consumption and the cost-effective deployment of the connectivity infrastructure. VLC can provide wireless data connectivity in environments where the use of RF is undesirable, unsecure, or impossible. VLC technology can introduce unique key features into the 6G infrastructure, helping to make 6G a ubiquitous, sustainable, secure, and safe connectivity fabric.

A typical indoor application of VLC involves multiple LED light bulbs that form a wireless communication network, offering a similar connectivity experience to Wi-Fi. VLC provides a high-speed, secure, dense, and reliable wireless network for office and home environments, and acts as an enabler for smart buildings and smart cities.

For outdoor applications, VLC technology can easily be implemented in automotive communications, where cars and traffic lights can be used to transmit data for control or emergency information. The VLC system allows the creation of an attocell network between infrastructure-to-vehicle (I2V) or vehicle-to-vehicle (V2V) for ultra-low latency communications [NSC19]. The visible light network can work with a wider RF cell to increase the capillarity of the network (see Figure 9.1). Moreover, the VLC can extend the use of the IoT, even in critical environments where RF cannot be used (hospital, airplanes, underwater).

9.3 Related system architecture

We next present some possible research directions for future OWC system architectures. The main OWC technologies, namely VLC, light fidelity (LiFi), optical camera communication (OCC), and FSO are considered “direct emission” types. The light sources are directly exposed to the wireless channel. VLC and LiFi both use a visible light spectrum for a downlink, whereas LiFi takes VLC further by realizing fully networked wireless systems. This includes bidirectional multiuser communication and full user mobility. OCC uses a camera or image sensors to receive the optical signal. If equipped with an LED array and an optical lens to distinguish the images of LEDs in the image sensor, an OCC system follows a massive MIMO configuration. FSO incorporates very narrow laser beams, which decrease the amount of geometrical path loss. An LED has a very wide modulation bandwidth (up to tens of GHz), which makes the FSO a viable solution for high-speed point-to-point wireless communications. However, accurate beam tracking and pointing is required for FSO to maintain the alignment between the transmitter and receiver.

Radio-over-fiber (RoF) technologies have been developed, in which conversion from the optical to electrical domain is required at the far end. An all-optical approach has been proposed, in which the wireless signal is kept in the optical domain and fiber-based transceivers are used at both ends of the wireless link. The corresponding fiber-wireless-fiber (FWF) link is independent of the data rate and modulation format. Coherent modulation and demodulation, which is widely used in optical fiber communication and RoF, can be used in hybrid fiber-wireless OWC.

Laser-based simultaneous wireless information and power transfer (SWIPT) technologies can achieve a high bit rate. However, they usually face the challenges of mobility and eye safety. Resonant beam charging (RBC), also known as distributed laser charging (DLC), has been proposed for wireless power transfer (WPT) with intrinsic safety, high power, and a self-alignment capability [XLL19]. In the RBC system, two retro-reflectors embedded in the transmitter and receiver enable mobility. Meanwhile, the high-power beam of RBC can play the role of information carrier for optical communications.

Backscatter communication has been used in radio systems (e.g. RFID), as well as in OWC. Like RFID systems, in which a load modulator is equipped at the tag to modulate the reflected interrogating signal in the optical backscattering system, a modulating retro-reflector (MRR) is used to retro-reflect the modulated light back to the interrogating source [YLB17]. There will thus be no requirement of a local laser source, and a corresponding beam-tracking and pointing ability, leading to low power and complexity design.

In summary, extensive research has been carried out on direct emission OWC, hybrid fiber-wireless OWC, spatially distributed laser cavity-based SWIPT, and optical backscatter communication. The direct emission OWC can be adopted in joint illumination and communication scenarios. Hybrid fiber-wireless OWC can also be easily integrated with existing optical fiber networks, making it an attractive option for high-speed indoor wireless access. The spatially distributed laser cavity-based SWIPT has been demonstrated to be the only intrinsically safe, long-range, watt-level wireless charging solution so far, while in the meantime, it is capable of establishing an optical communication link between the transmitter and the charged device. Finally, an optical backscatter with a low power and complexity feature can be used for power-constrained scenarios such as wearable and IoT devices.

Toward realistic/ feasible system concepts 10

Implementing a wireless system always entails a tradeoff between many factors. Advances in different technology areas, including RF, must be evaluated over technology boundaries and against requirements from use cases. Generic goals like sustainability and economic aspects must also be considered. This does not actually differ greatly in 6G from previous generations, but increased opportunities and various requests for technical capabilities make the analysis even more complex than before.

It is necessary to revise some of the very fundamental principles that are as valid as they were in the first generations of wireless personal communications. However, due to complexity and the wishes of different involved parties, many will easily be ignored, or at least their relationship with system success will be difficult if not impossible to analyze at an early phase in a balanced way. Many key decisions concerning future standards may therefore happen with a limited view of physical boundaries, for example, power consumption. Of course, this is not the preferred general approach.

All wireless communication networks operate under three primary constraints, with the values of these constraints determined by the application the wireless communication network serves. These constraints, presented in Figure 10.1, are the availability of spectrum within which to operate, the availability of power to operate the network, and the availability of sufficient funds to undertake three essential activities: 1) gaining access rights to the spectrum; 2) installing the network (capital expenditure, or capex); and 3) operating the network (operating expenditure, or opex).

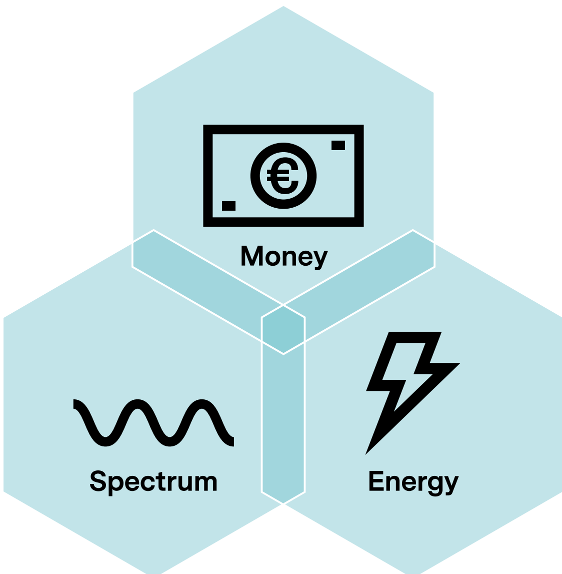


Figure 10.1. Wireless communication networks operate under three primary constraints: spectrum availability; energy availability; and the availability of sufficient funds to both install (capex) and operate (opex) the system.

Above all, it is essential that 6G is profitable to manufacture, install, and operate. Technologies must be used to serve the various 6G applications, whether or not they are well known, in the most cost-effective manner. For example, the present 5G mmW transmitters operate using the 3GPP standardized modulation, with an operating power efficiency in the order of 2%. This low operating efficiency is fully understood, and is an artifact of the present transistor technology that is available at these frequencies. This low efficiency means that the corresponding power supply to the transmitter is 50 times greater than the realized transmitter signal power, of which 98% is directly converted to heat to be absorbed by the heat sink. Such proportionally large power supplies and heat sinks are expensive to manufacture and add to weight, making installation more expensive, and the large power draw once installed is a continuous operating expense. Such a situation must be avoided in 6G.

Efficacy, the effectiveness of how many bits can be moved using energy inputs (measured in joules) of any digital wireless link can be described by the relationship shown in [CUN19]. This paper demonstrates how signal modulation, hardware, channel environmental, and physical parameters all interrelate. These parameters are not independent of each other. In particular, requirements for circuit linearity, a higher operating frequency, and very long-distance communication (like satellites) or communication through occluded environments are strong influences in reducing wireless link energy efficacy, requiring more energy to move the necessary bits.

The strong and complex dependence of hardware properties against achievable link range should not be omitted, because it will be easily undertaken during the early phase of wireless system development. It is of the utmost importance to understand that these are fundamental tradeoffs in system design and hardware implementation––nothing comes for free. The key aspects of many of these tradeoffs are described next.

Carrier frequency: As frequencies of interest increase, the path loss increases for equivalent antenna patterns. Path loss can be constantly maintained across the frequency only when antenna directivity becomes correspondingly tighter (leading to both antenna-aiming requirements and a loss of inherent coverage area). On the other hand, the available signal bandwidth increases as a function of frequency, which increases the available f_{sym} and/or subcarrier count *N*. This is due both to the less occupied spectrum and an absolute bandwidth increase with respect to the carrier, while the relative bandwidth of RF circuits remains constant. This relativity is a fundamental property typical of RF circuits.

Transistors all have internal limits to the speed at which they can operate, and the closer we choose to operate to these speed limits, the less any transistor provides of the desirable properties of linearity and gain. Operating at higher carrier frequencies will therefore be inherently more expensive until the technology provides transistors with higher speed limits. The increased absorption of higher frequency signals by the atmosphere will add further cost to links at frequencies above 100 GHz.

Data rate––bits per symbol: Shannon showed that bandwidth efficiency is improved by using more bits within each symbol, accessed by having a sufficiently high link signal to noise power ratio (SNR). Encouraging this is the economic reality that while service providers use the spectrum, they sell data-rate performance. The bridge between the occupied spectrum and data rate when the spectrum is limited is to increase the bits per symbol.

Fortunately, the necessarily high link SNR is easier to achieve when antenna directivity increases. Antenna directivity is key to the massive MIMO feature of 5G, so this path is already happening. Interestingly, while these higher-order signals definitely increase the link data rate, they also require higher SNR in the receivers. Unless this SNR increase is achieved by increasing antenna directivity, the link energy efficacy in [CUN19] shows that the increased signal order is neutral from an energy perspective.

Modulation types: Signal envelope i.e. peak-to-average power ratio (PAPR) and multicarrier modulations (which further increase PAPR) are the two primary drivers of the present very high power consumption in 4G and 5G transmitters. To reverse this energy-draw trend, it will be necessary to develop and adopt modulation types that have the same number of bits per symbol, but are single carrier and have PAPR below 4 dB. Such signal modulations do exist, and their use is key to meeting service providers' capex and opex requirements.

Other opportunities may exist, especially in finding and developing the additional degrees of freedom available to signal modulation. One such possibility is orbital angular momentum (OAM), which warrants further study and hopefully, development.

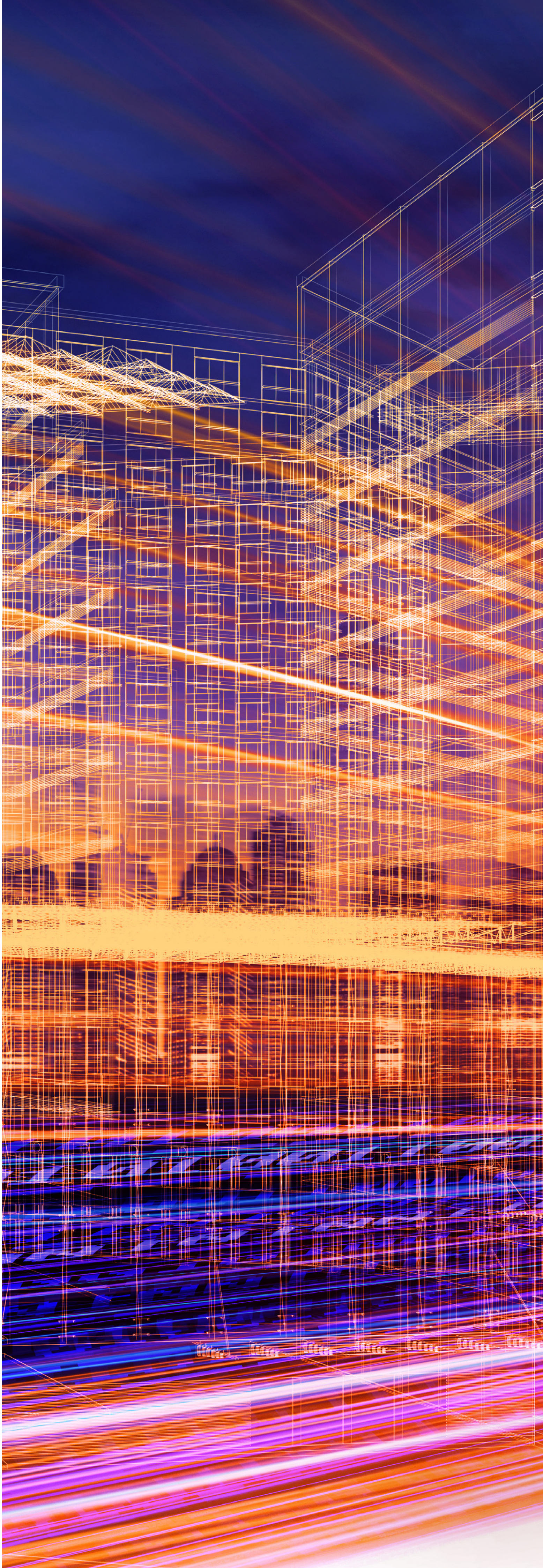
Data rate––symbol rate/signal bandwidth: For single-carrier signals, Nyquist showed that the dominant determination of signal bandwidth is the modulation symbol rate. For multicarrier signals, the signal bandwidth is effectively the product of the modulation symbol rate per carrier and the number of carriers, N. For fixed bandwidth efficiency, the data rate can only be increased by using more spectrum. This is precisely the driver behind 4G carrier aggregation (CA) and the wider signal modulation bandwidths in 5G. Because modulation bandwidth maps directly onto spectrum use, any further increases in data rate through the modulation bandwidth must occur in new spectrum allocations (e.g. within 30–300 GHz). Reducing the expense (financial and in power) of operating at these frequencies is vital to making such frequencies profitable to use––which, at the time of writing, they are not.

Antenna types: The above discussions indicate the importance of antennas for realizing the communication goals of 6G (and 5G). The antenna size is set by the carrier wavelength, while antenna effectiveness is set by absolute size. This is the fundamental tradeoff for this part of the communication link.

Three antenna types are known to provide excellent directivity performance: reflector; array; and lens. Their historical application is of the same order. Modern lens techniques are low loss and very directive (~3 degrees), and do not require the coordination of many antenna elements across an array. It may be valuable to consider multiple fixed beams from lenses alongside multiple steered beams from antenna arrays to explore which applications of each technique provide the best energy efficacy for 6G.

Coverage and mobility: Coverage is presently provided by flooding the service area with signal power density sufficient to guarantee receiver operation, no matter where it is, or how it is moving. This strategy thus wastes nearly all the transmitted signal power from the network infrastructure, but provides an acceptable service. Shifting to directed communication to save on transmitted power necessarily reduces coverage to small areas, and requires beam steering to fill in coverage holes, and tracking to provide mobility once a link is established. Power saved from radio transmitters is (partially?!) shifted to digital background processing. The optima of this transition need exploring for 6G.

Merged services: Communications provide data transfer in spite of channel conditions, and radar uses known data to identify channel characteristics. Both use radio techniques, with very different objectives but with very similar implementing hardware. The possibility of combining these two services through time sharing is tantalizing, because hardware reuse can save on total power for all 6G services.



Concluding remarks 11

RF and in general HW and the physics around radios is currently only one aspect of future communications and sensing systems, in which wireless operations will play an ever-increasing and important role. Yet the technologies we can build around these constraints define what is possible, and what is not. External expectations are often unrealistic, and decisions in the worst case will be made without understanding the consequences. However, we can and will implement only systems that can be implemented, and only those which are commercially or sometimes politically beneficial will ultimately survive. In recent decades, we have seen that visions that sometimes sounded completely unrealistic ultimately materialized and became a commodity. Balancing the possible and impossible will therefore also play an important role on the path toward 6G. Interplay and mutual respect between RF and electronics, wireless, networking, and software communities are needed. All are necessary and important components of our future systems.

In this paper, experts from the various disciplines around RF research and industry have shared their technological understanding, with views of different aspects and details considered highly relevant not only inside the community, but that are of broader importance on the journey toward 6G, and even beyond. The deep technology insights are introduced in this context to provide a background for the claims and conclusions. We hope they will offer many useful insights for addressing relevant questions that in many ways sound even tougher for 6G than for some earlier generations in the evolution of digital communications systems. The list of relevant questions is almost endless, and each can be split into dozens or hundreds of valuable details for researchers and engineers in academia and industry to solve. Some are listed below. Not all of them are technical, but they also raise challenges for how these systems should be build when targeting an optimum, which may be performance, data rate, power consumption, a combination of them, or anything else that will support society. Such a list can never be comprehensive, but it is hoped it is sufficiently broad to cover the most topical items to be addressed in 6G research.

Some research questions for the community:

1. What are the feasible RF, HW, and related SW technologies in the foreseeable 6G timeframe?
2. How can a unified 6G channel model from GHz to THz be created?
3. What are the feasible bands and technologies >100 GHz?
4. How can HW-friendly and spectrally efficient waveforms be defined?
5. Where can 6G spectrum be allocated, and with what policies?
6. What roles do electrical and photonic technologies play in 6G?
7. What is the achievable silicon-based technology performance in THz/Tbps systems?
8. What are other necessary or highly potential technologies and materials?
9. How much power can be generated in the upper mmW region?
10. How low a noise can we achieve in the upper mmW region?
11. How can steerable antenna arrays >100 GHz be implemented?
12. How can tunable antennas and other RF solutions be controlled and utilized in machine learning?
13. How can the coexistence of communications, sensing, substance detection, and imaging in the THz region be achieved and implemented?
14. How can 6G be kept sufficiently simple for Tbps?
15. How can future wireless systems be tested efficiently and reliably, from details to systems?
16. What kind of sharing mechanisms are needed in the different spectrum bands?

17. How can spectrum sensing be included as part of radio design to expolit low-cost and wideband spectrum monitoring?
18. How can we address very low power radios as part of the 6G system? Should we?
19. When will energy harvesting from any source for radio operations make sense, and what techniques might be scalable for longer range or higher data rates, if any?
20. What are the selection mechanisms and criteria for selecting the right radio for each application?
21. How can industrially viable and profitable radio systems be realized in the future?
22. What will we need in the future to master the engineering process when software, computing, communications, and electronics need to cooperate better without a common language?
23. What will it mean to make tradeoffs wisely?
24. How can complexity within the RF/HW community be managed, as well as with the rest of the industry/academia?
25. What questions did we forget?

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White Paper on RF Enabling 6G – Opportunities and Challenges from Technology to Spectrum

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